Are we ready for the invasion of Tuta absoluta? Unanswered key questions for elaborating an Integrated Pest Management package in Xinjiang, China

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Are we ready for the invasion of *Tuta absoluta*? Unanswered key questions for elaborating an Integrated Pest Management package in Xinjiang, China

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With 1 figure

Abstract: The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is an invasive destructive pest of tomato and other solanaceous plants. Since its first detection in Spain in 2006, the pest has started its invasion across the Afro-Eurasian super-continent. Xinjiang Uyghur Autonomous Region of China, adjacent to the recently infested central-Asia countries, being the largest tomato growing region worldwide, is now under high invasion risk. Considering the importance of this issue, we must plan ahead to be fully prepared for the potential invasion of this pest in near future. In this paper, we call for upcoming studies to address several aspects including the overwintering biology, diapause, dispersion, population ecology in outdoor crops and insecticide resistance of invading populations. Moreover, the effective management options are proposed based on the control experience in its native range and recently infested countries. Our "look-ahead" proposal not only serves as a guideline for

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elaborating the pest management strategy in Xinjiang in near future, but can also interest the rest of the tomato-producing regions worldwide that have not been infested yet by the moth.

Keywords: solanaceae plants, overwinter, diapause, dispersion, insecticide resistance, biological control, mating disruption

1 Introduction

The South American tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is one of the most devastating pests of tomato (Desneux et al. 2010, 2011, Biondi et al. 2018). Damage is caused by larvae feeding on the leaves, stems and fruits of tomato plants, thus decreasing yield and making the fruits unsuitable for the market. Since its first detection in Spain in 2006 (Biondi et al. 2018), the South American tomato pinworm has spread rapidly throughout Europe, Africa, the Middle East and parts of Asia with severe damage to local agriculture and environment (Campos et al. 2017). The species is considered as a major agricultural threat to tomato production in both greenhouse and outdoor tomato crops (Desneux et al. 2010, 2011). More recently, *T. absoluta* poses a high invasion risk to China, especially to Xinjiang Uyghur Autonomous Region (thereafter as "Xinjiang") which has geographical proximity with the infested Central Asia countries (Xian et al. 2017). The moth also threatens southwestern China as it has been detected in India (Sankarganesh et al. 2017).

Biological invasion and management of agricultural invasive alien pests have become an increasing challenging issue worldwide (Ragsdale et al. 2011, Wan & Yang 2016, Abram et al. 2017, Lavrinienko et al. 2017). Xinjiang, northwestern China, is one of the largest tomato growing areas and an important transportation hub, which produces over 30% of the of processing-tomato worldwide (Xian et al. 2017). The ever-increasing international fruit trade is one of the potential introduction pathways. The regional climate, agricultural landscape and cultivation pattern of cropping system in Xinjiang are unique and vary substantially in comparison to the conditions of the countries where the pest is already present. Notably the pest requires high adaptation capacity to local extreme climate conditions, e.g., low temperatures in winter and dry/hot conditions in summer (Wu et al. 2010). However, this species has been shown to have high coldness tolerance (Van Damme et al. 2015) as well as high adaptation to dry and hot conditions. The latter is supported by the fact that it has invaded from northern Africa countries to South Africa over two to three years (Biondi et al. 2018, Mansour et al. 2018). Therefore, an Integrated Pest Management (IPM) package should be elaborated in advance to be prepared for its potential, but very likely, occurrence in Xinjiang. Such efforts could be helpful for minimizing its damage and spread in this region in near future. In this paper, we call for future studies on overwintering biology, diapause, population dynamics in outdoor crops and insecticide resistance management of potential invading populations.

2 Proposed future research priorities in Xinjiang

Here we propose a framework showing the potential future research priorities on *T. absoluta* in Xinjiang (Fig. 1). Addressing several key questions may help elaborating an IPM package in case of *T. absoluta* invasion success and pest outbreaks in this region.

2.1 Does *T. absoluta* overwinter and diapause in open fields?

Knowledge on overwintering capacities of *T. absoluta* in Xinjiang can suggest correct timing for implementing control measures against this pest. In the case of the species population detection in tomato open fields, the first question to be answered is whether it is capable of overwintering in open fields. Several studies have shown its overwintering capacity at low temperatures in both native and invaded regions (Rolando et al. 1998, Cuthbertson et al. 2013, Van Damme et al. 2015). In early tomato growing season, *T. absoluta* was present in 43% of the forty-seven surveyed sites in February in Flanders (Belgium) (Van Damme et al. 2015), suggesting that the pest might be able to overwinter in or in close proximity to protected tomato crops. This would corroborate the hypothesis made by Potting et al. (2013) that this species can survive and establish in protected cultivation in North Western Europe. We also observed high population density of this pest in open fields in Tajikistan and Uzbekistan in 2017 (unpublished, Lu ZZ). EPPO (2005) also reported that this pest can survive temperatures slightly below zero degrees for a short period in North Western Europe. In the case of Xinjiang, despite the average temperature often goes to −20° C in most areas, the soil and the

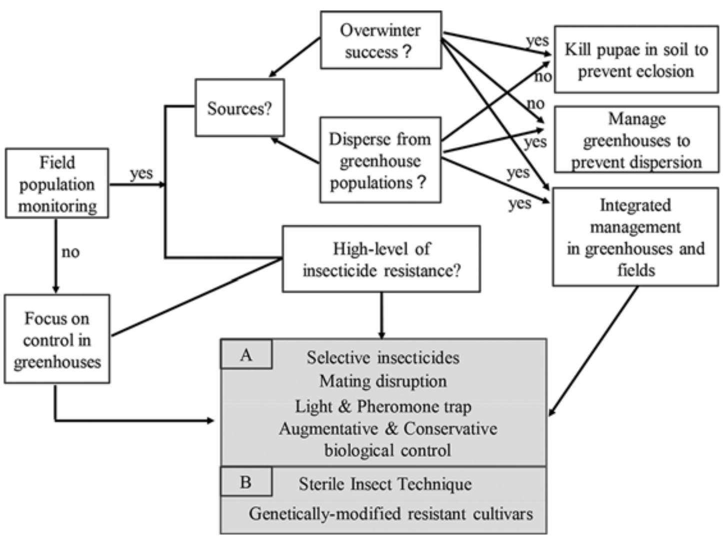

Fig. 1. The framework showing the prospective research proposal on *T. absoluta* in Xinjiang, China. The direction of arrows indicates the workflow.

eventual residual host plants (wild and cultivated) infested by the pest can be covered by snow in early winter, having thus a higher temperature than the external conditions for several months. This condition may stimulate insect diapause and thus favor the overwintering success of *T. absoluta* pupae.

Diapause is an adaptive mechanism for insects to tolerate adverse conditions. Desneux et al. (2010) mentioned that if host plants are available and climatic conditions are favorable, larvae feed almost continuously and generally do not enter diapause. The diapause potential in *T. absoluta* has been overlooked since long until recently Van Damme et al. (2015) has examined such a potential. However, no evidence of reproductive diapause has been observed in this study. It has also been reported that the optimum temperature for *T. absoluta* was 30 °C with upper and lower developmental thresholds of 34.6 and 14 °C, respectively (Martins et al. 2016). It should be noted that the threshold of low temperature does not denote that the individuals experience high mortality under 14 °C, as they can tolerate much lower temperatures as shown by Van Damme et al. (2015). Therefore, the cold hardiness and diapause responses of *T. absoluta* need to be predicted in Xinjiang, aiming to obtain the knowledge of its overwintering potential in open fields and the risk of population build-up during early season.

2.2 Does *T. absoluta* disperse from infested greenhouses to build up populations in open field?

To be continued with the previous assumption that *T. absoluta* populations are detected in open fields, our another question would be whether adults disperse from the infested greenhouses to adjacent open fields for building populations? Tomato is the election host-plant for *T. absoluta*, and the moth can also feed on other cultivated solanaceae crops, such as eggplant (*Solanum melongena* L.), potato (*S. tuberosum* L.), sweet pepper (*S. muricatum* L.), tobacco (*Nicotiana tabacum* L.), as well as the wild species such as *S. nigrum* L. (Biondi et al. 2018). The pest shows high morning-crepuscular activity with adults moving towards tomato crops by flying, indicating that *T. absoluta* shows a high propensity to use various plant species as secondary hosts to disperse (Desneux et al. 2010). Data from sampling with pheromone traps and spatial assessments suggests a high dispersal capacity in this moth (Gontijo et al. 2013). This gives us an idea that we can assess the dispersion of *T. absoluta* populations in nature to figure out whether they often disperse from infested greenhouses to open fields. Insect marking might be a useful tool to track the movement of *T. absoluta* populations (Hagler & Jackson 2001). For instance, tomato experimental crops can be contaminated by the trace amount of microelement Rubidium and the exposed moth can be tracked to estimate their dispersal capacity (Klick et al. 2015).

2.3 What are the suggestions for upcoming chemical control? Insecticide Resistance Action Committee (IRAC) guidelines

Chemical control is the most important tool in suppressing *T. absoluta* since its dispersion in South America over the 1970s. However, reports of control failure have clearly demonstrated the high resistance of this moth to multiple classes of insecticides (Siqueira et al. 2000, 2001, Haddi et al. 2012, Roditakis et al. 2018). Reports from Chile, Argentina and particularly Brazil suggest that insecticide resistance evolves quickly in this species as an intrinsic response to insecticide use or overuse (Siqueira et al. 2000, Lietti et al. 2005, Silva et al. 2011, Guedes & Picanço 2012, Campos et al. 2015). In Brazil, tomato growers carry out up to 36 times of insecticide applications to control *T. absoluta* within one cropping season (Guedes & Picanço 2012). As a result, resistance of *T. absoluta* to abamectin, cartap, methamidophos, bifenthrin, permethrin, chitin synthesis inhibitors, triflumuron, spinosad and teflubenzuron was reported in Brazil (Siqueira et al. 2000, Salazar & Araya 2001, Liettiet al. 2005, Silva et al. 2011), while resistance to abamectin, deltamethrin and methamidophos was also detected later in Argentina (Lietti et al. 2005). Resistance to organophosphates and pyrethroid insecticides was reported in Chile (Salazar & Araya 1997, 2001). More recent studies have shown that *T. absoluta* populations in South America and Afro-Eurasia can genetically develop resistance to novel insecticides, including pyrrole chlorfenapyr, spinosyn spinosad, diamides chlorantraniliprole and flubendiamid (Guedes & Siqueira 2012. Campos et al. 2015, Roditakis et al. 2015, 2018). In addition, *T. absoluta* has been shown resistant to pyrethroid before its introduction into Spain in 2006 (Haddi et al. 2012).

Additional factors such as toxicity testing protocols, larval stages, weather condition, spraying frequencies and the spatial distribution of *T. absoluta* may lead to different findings (Siqueira et al. 2000, Silva et al. 2011, Gontijo et al. 2013, Roditakis et al. 2013). Existing data shows that *T. absoluta* has developed high resistance to several most popular insecticides, thus hinting that the individuals (invading from the West) that will enter into Xinjiang may already bear high resistance to those insecticides. Another notorious pest, the whitefly *Bemisia tabaci* (Hemiptera: Aleyrodidae), showed high resistance to several commonly-used insecticides such as pyrethroids when it was initially detected in Xinjiang (Ma et al. 2007). Such a consequence may be linked to historical overuse of insecticides in this region since late 90s. For the case of *T. absoluta*, it is practical to avoid using those "ineffective" insecticides. More importantly, local growers are suggested to rely on IRAC (Insecticide Resistance Action Committee) guidelines for adopting insecticide resistance management (IRM) strategy (e.g. rotation in use of different Mode of Action (MoA) chemicals, the issue of cross-resistance, etc.). Moreover, it could be beneficial to run the spatial-analysis of invading pest population's insecticide resistance and thus map the areas with high risk of chemical control failure in future.

2.4 What are the recommendations for management of this pest?

Insecticides will be surely used once the emergent outbreak of this moth occurs in a given area. Such efforts could prevent further spread of the moth. For our case, commonly-used commercial insecticides should firstly be registered before its invasion success. With increasing concerns over the long-term adverse environmental impact of some chemical pesticides and their rising costs, another important task is to determine the economic injury level (EIL) (i.e. action threshold) of this moth in Xinjiang (Balzan & Moonen 2012). This information could be helpful for growers to make decisions whether chemical control is needed once they detect larval infestation in greenhouses and/or open fields.

Overuse of insecticides has several flaws including high insecticide resistance of the moth (Guedes & Picanço 2012, Campos et al. 2015, Roditakis et al. 2015, 2018), low toxicity effects due to cryptic nature of the larvae (Campos et al. 2017), and potential side effects on arthropod pollinators and natural enemies (Desneux et al. 2007, Han et al. 2012, Decourtye et al. 2013, Biondi et al. 2015, Perez-Aguilar et al. 2018), including fortuitous natural enemies of *T. absoluta* that belong to the Chinese fauna (Abbes et al. 2015, Biondi et al. 2013a, Martinou & Stavrinides 2015). Therefore, alternative management options, such as mass trapping, mating disruption, the use of selective insecticides and biological control have to be prioritized because they are considered sustainable and effective (Desneux et al. 2005, Vacas et al. 2011, Cocco et al. 2013, Caparros Megido et al. 2013, Loboset al. 2013, Zappalà et al. 2012, 2013).

In the case of low population densities, mass trapping by using pheromone baited water traps has shown to be effective in Spanish (an average of 30–40 pheromone baited water traps placed per hectare) (Aksoy & Kovanci 2016). Compared with the control, mating disruption against *T. absoluta* using 1000 dispensers/ha can reduce the percentage of males by 93–97% and damaged fruits by 62–89% in greenhouses (Cocco et al. 2013). Therefore, the mating disruption technique against *T. absoluta* in open field crops should be tested in area-wide open fields, but with costs considered. The effectiveness of mass trapping using light traps to control *T. absoluta* was investigated in southwestern Sardinia, Italy (Cocco et al. 2012), which reported that this tool can reduce significantly the leaf damage at the density of 1/500m^2 or 1/350m^2 when *T. absoluta* has a low/moderate population density during the summer-winter season, whereas such management option did not work in winter-summer season. It indicates that the local season should be considered when using light traps to control *T. absoluta.*

Various indigenous natural enemies have been recorded targeting *T. absoluta* eggs, larvae and pupae, in both native and invaded areas (Biondi et al. 2013b, 2018, Zappalà et al. 2013, Calvo et al. 2016, Salehiet al.2016, Campos et al. 2017). Several species, for example the generalist parasitoid *Bracon nigricans* (Hymenoptera: Braconidae) and the omnivorous bugs *Nesidiocoris tenuis* and *Macrolophus pygmaeus* (Heteroptera: Miridae), have been considered as promising agents to keep low population of the pest (Jaworski et al. 2013, 2015, Mollà et al. 2014). More specifically, *N. tenuis* is a commonly-used biocontrol agent in greenhouses in China (Zhang et al. 2015, as well as personal communication with Dr. Hou ZR from Beijing Plant Protection Station). As a consequence, it would be important to study the efficacy of inundation release of *N. tenuis* in suppressing the pest as well as the impact of habitat manipulation on conserving this predator within and/or close to tomato fields (Balzan et al. 2016, Biondi et al. 2016).

Moreover, significant progresses have been made on the commercial mass-rearing, maintenance, transportation and field-release of biocontrol agents over the last two decades in China (Liu et al. 2014). It would thus be appropriate to test the efficacy of other commercially mass-reared agents which have high potential for controlling *T. absoluta*, for example, Trichogrammatidae (Hymenoptera), Chrysopidae (Neuroptera), Anthocoridae (Hemiptera) and Phytoseiidae (Acari) (Zhang et al. 2015).

These tests may pay off since combined release of parasitoid and predator agents have been shown effective in reducing *T. absoluta* populations at least in protected crops (Chailleux et al. 2013). In addition, the commercial microbial formulations of *Bacillus thuringiensis* (Bt) Berliner and the entomopathogenic fungus *Beauveria bassiana* (Balsamo) Vuillemin are considered alternative efficient control options. Gonzalez-Cabrera et al. (2011) reported that the commercial formulates reduced *T. absoluta* damage up to 90% when sprayed at 180.8 MIU/l, while greenhouse tests showed that even weekly *Bt* sprays at 90.4 MUI/l were able to control *T. absoluta* throughout the growing season in Valencia (Spain). The entomopathogenic *B. bassiana* fungus caused larvae mortality up to 95% compared to chemical treatment at 88% (Elkichaoi et al. 2016).

If *T. absoluta* population will not be detected (or very few) in open fields in Xinjiang, the management efforts will solely focus on greenhouse populations. Pheromone-based mass-trapping, mating disruption and release of biocontrol agents should be combined as an efficient IPM package. In case that a relatively high population will be detected in field, the source of the population should either base on on-site overwintering success of the individuals or dispersion from adjacent greenhouse populations. Mulch film could thus be useful during the early season to prevent adults from escaping after eclosion in the former case. By contrast, if evidences will be acquired about the ability of *T. absoluta* to disperse from greenhouses to fields in the late spring when it is getting warmer outdoors, tomato and other solanaceae crops are not recommended to be cultivated in March and April, leaving a two-month mortality window for *T. absoluta*. Moreover, strict sanitation in greenhouses is crucial for preventing the population dispersion into fields and/or between greenhouse cropping cycles. In case that *T. absoluta* succeeds in building populations on transplanted crops in fields, the elimination of symptomatic leaves, destruction of infested tomato plants and use of sex pheromone-based mass trapping are highly recommended during the early season to limit the population growth. The impact of alternative agronomic practices including specific fertilization regimes (Han et al. 2014, 2016a, Larbat et al. 2016, Dong et al. 2017, Blazhevski et al. 2018) and soil features (organic substrate and/or biofertilizers) (Mohamadi et al. 2016) on the biology, demography and ethology of *T. absoluta* should be considered when building the IPM package. As Xinjiang is one of the most typical arid regions being characterized with high salinity in soil and/or ground water (Wang et al. 2018), caution thus needs to be taken if saline water will be used to irrigate tomato crops. It has been shown that saline water applied to tomato plants can accelerate the development of *T. absoluta* without lowering their pupal weights (Han et al. 2016b).

Besides the current management options, emerging techniques need to be developed in future (as shown in Fig. 1). The sterile insect technique (SIT) is one of the promising options as we have witnessed many successful cases of lepidopteran pests (Simmons et al. 2010). However, little is known about this aspect of *T. absoluta* except for one study (Cagnotti et al. 2012). In this study, the minimum doses were explored for triggering inherited sterility by X-radiation, with the appearance of deformities such as malformed wings and bent legs at doses ≥ 350 Gy and inherited sterility in *T. absoluta* adults at doses between 200–250 Gy, respectively. The quality and field performance of the released sterile moths need to be characterized in future works. Nevertheless, this direction is challenged by the evidence of deuterotokous parthenogenesis reported for this species (Caparros Megido et al. 2012). In addition, great efforts have been made to select or breed insect-resistant varieties against *T. absoluta* (Sohrabi et al. 2016, Ahmed et al. 2017, Selale et al. 2017). Development of transgenic *Bt* tomato lines may have great potential for area-wide adoption following the successful case of *Bt* cotton in China (Lu et al. 2012).

3 Conclusion and future outlook

Since the tomato pinworm *T. absoluta* was firstly detected in Spain in 2006, its presence has been recorded in more than 80 countries around the world until 2017. This species is currently posing high invasion risk to China. Based on existing knowledge of biology, ecology and management of this moth in infested countries, we provide a framework showing how we should be prepared for its invasion. We propose a novel specific IPM package including (i) a regional inspection network by setting pheromone traps in Xinjiang bordering areas, (ii) an emergent control procedure once the moth will be detected in Xinjiang, and (iii) an IPM package including pheromone-based mass-trapping, mating disruption, conservation of wild indigenous natural enemies and inundation release commercial biocontrol agents. Our “look-ahead” proposal in this paper will not only help prevent biohazard of this species in China, but may also interest the other tomato-producing regions of the world – notably Australia, Canada, Mexico and the United States.

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