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The potential invasion risk and preventive measures against the tomato leafminer *Tuta absoluta* in China

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With 3 figures and 1 table

Abstract: The tomato leafminer, *Tuta absoluta*, a serious pest threatening the tomato industry in South America, Africa, Europe and Central-West Asia, now has recently invaded the neighboring countries of Northwest and Southwest China. With the increasing international trade in agriculture products, *T. absoluta* presents a potential threat to Chinese tomato and potato industry. In order to effectively prevent the introduction of *T. absoluta* and strengthen the alertness of plant quarantine staff and agricultural researchers against this pest in China, we evaluated its potential introduction pathway, host plant species and climate suitability, and also reviewed the monitoring measures being carried out in China. Finally, potential integrated pest management strategy for *T. absoluta* in China was proposed based on the management experience of *T. absoluta* in the origin and invaded countries. This will assist Chinese policy-makers to improve current surveillance, phytosanitary measures as well as future management strategies for *T. absoluta*.

Keywords: tomato leaf miner, invasion risks, quarantine, Integrated Pest Management, biological control

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1 Introduction

The tomato leaf miner, *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae), originated from South America, has become a devastating pest of world tomato industry (Desneux et al. 2011). Since *T. absoluta* was firstly detected outside its native areas (i.e. Spain, 2006), it has rapidly spread across the national borders within Europe, Africa, West and Central Asia in the following years (Desneux et al. 2010). Until 2016, its presence has been recorded in more than 80 countries around the world (Campos et al. 2017). Solanaceous species are the important host plants of *T. absoluta*, with tomato (*Solanum lycopersicum*), potato (*S. tuberosum*) and bell pepper (*Capsicum annuum*) being the main hosts (Desneux et al. 2010, Bawin et al. 2015, 2016, Invasive Species Compendium, CABI 2017). Other alternative host plants species belong to Amaranthaceae, Convolvulaceae, Fabaceae and Malvaceae families (Desneux et al. 2010, Ferracini et al. 2012). If no prevention and control measures are taken in time, the pest can cause up to 80–100% yield losses in tomato crops in recently invaded areas and pose a threat to tomato production in both greenhouse and open-field throughout the season (Desneux et al. 2010).

Tuta absoluta, first reported in Spain (2006) have spread extremely rapidly and invaded most of Europe and Mediterranean countries within a few years (Roques et al. 2016). In the case of *T. absoluta* invading in Asia, the pest spent only about 7 years spreading from the Mediterranean countries to the West and Central Asia (Campos et al. 2017). In 2009, this pest was only present in Asian countries along the Mediterranean Sea, such as Israel, Turkey and Kuwait (Seplyarsky et al. 2010, Kılıç 2010, Campos et al. 2017). From 2010 to 2014, it had invaded further into the Arabian Peninsula including Iran, Iraq, Saudi Arabia, and Syria in 2010 (Baniameri & Cheraghian 2012, Abdul-Rassoul 2014, Almatni 2010, Ibrahim et al. 2012), Jordan, Lebanon and Qatar in 2011 (Al-Jboory et al. 2012, Al-turaihi 2014, Campos et al. 2017), United Arab Emirates in 2012 (Campos et al. 2017), as well as Yemen in 2013 (Campos et al. 2017). Afterwards, the pest started to cross the Persian and Oman Gulfs, and landed on the Indian peninsula (Sridhar et al. 2014, Bajracharya et al. 2016, Hossain et al. 2016, Campos et al. 2017). Thus, the presence of this pest was reported in India (2014), Afghanistan and Turkmenistan (2015), Nepal and Bangladesh (2016). Additionally, there were also some uncertain reports in Pakistan, Tajikistan, Kyrgyzstan, Uzbekistan and Myanmar (Campos et al. 2017). To effectively prevent the introduction of *T. absoluta* in their territories, Pakistan has added this pest into the List of Quarantine Harmful Organisms of Phytosanitary Concern in 2016 (www.tutaabsoluta.com 2016).

Tuta absoluta is in the border of Western China now. The traditional and regular ferry services of passengers and goods across the ports between West-Central Asian countries and China present a potential invasion bridge for this pest. With the implementation of “the Belt and Road Initiative” led by China, the international trade and tourism between China and Eurasian countries through Western China will be further promoted (Zou et al. 2015). Since the above-mentioned Asian countries with *T. absoluta* presence are the key nodes along the trading routes, we suspect a high chance that this pest enters China in upcoming years. The provinces Xinjiang, Neimenggu and Gansu, adjacent to the invaded countries, are one of the largest tomato growing areas in China (China Rural Statistical Yearbook 2011–2015, http://data.cnki.net). Particularly, Xinjiang is also an important transportation hub and cargo distribution center between Central-West Asia and China. The large increase in the number of foreign animal and plant products, and international tourism in Xinjiang, may favor the introduction risk of exotic pests. Once it invaded China, *T. absoluta* will cause serious economic losses to the tomato and potato industry in China. Fortunately, there had been no report of its presence in China until the end of 2016.

To prevent *T. absoluta* from entering China or delaying its introduction, Chinese agricultural researchers and administrative staff have carried out early-warning monitoring plan of this pest since 2014, and the potential introduction and establishment risk analysis for *T. absoluta* have also been conducted. In order to improve the awareness and alertness of this invasive insect, the potential invasion pathway, probability of establishment, the progress of monitoring plan, and available control measures in China are summarized in this study.

2 Potential invasion pathway

According to the invasion history of *T. absoluta* in Europe, Africa and Asia, it can travel via several pathways (Desneux et al. 2010, Tonnang et al. 2015). The long-distance transmission mainly depends on the international agricultural trade. Tomato plants, fruits and used containers are known to be high-risk pathways for the introduction of this pest (Canadian Food Inspection Agency 2016). Besides, the greenhouses that repack and distribute tomato fruit produced in infested areas are one of the possible pathways. The infested soil is also a suspected pathway. Outdoor markets that sell tomatoes from infested areas and are located in places with suitable climatic conditions for the survival of *T. absoluta* also pose a risk (Canadian Food Inspection Agency 2016). Short-distance dispersal mainly depends on natural factors (such as wind or water), as well as crawling of larva and the flight of adult (Torres et al. 2001, Galdino et al. 2015). They are able to move between unscreened greenhouses and outdoor crops.

China has the largest tomato production industry worldwide with a large production of processed tomatoes and a small amount of fresh tomatoes exportation annually (China Rural Statistical Yearbook 2011–2015, FAO Statistical Database 2015). There is only 1 import record of fresh tomato fruits from aboard (from Italy to Beijing about 40 kg) by freight transportation into China since 2015, reported by China customs (http://www.haiguan.info 2017). By the end of 2016, there had been no interception record of the tomato leaf miner by General Administration of Quality Supervision, Inspection and Quarantine of China (http://www.pestchina.com 2016). However, the plant quarantine staff found that passengers on international flights often carry fresh fruits, including the cherry tomato fruits, from traveling countries. Generally, these fruits cannot be taken off the plane or will be interrupted during passing the custom inspection. Once illegal carrying is found, the companies designated by the plant quarantine department of local airport have to deal with these fresh goods. All related wastes should be centrally incinerated to guarantee the "zero leaking" of alien pests. However, there is also a possibility that these pests escape successfully and find suitable host plants around the airport before the infested fruits being processed. China also imported a large number of tomato seeds and a small amount of potato seeds from Europe and Asian countries annually (http://www.haiguan.info 2016). Fortunately, the introduction of *T. absoluta* by the seeds of tomato and sweet potato is very unlikely since the tomato seeds are imported in sealed packages or with pesticide coating and *T. absoluta* feed on the above-ground parts of potato rather than tubers.

3 Potential establishment

One of the key biotic factors favoring insect establishment in a given region is the suitability of host plant species. *Tuta absoluta* mainly feeds on tomato, potato and bell pepper (Desneux et al. 2011, Bawin et al. 2015, 2016, Invasive Species Compendium, CABI 2017). Crop species in the family Solanaceae such as peppers (*Capsicum* sp.), tobacco (*Nicotiana tabacum*), cutleaf groundcherry (*Physalis angulata*), eggplant (*S. melongena*), melon pear (*S. muricatum*) and *S. woronowii*, as well as some wild species of Solanaceae, such as jimsonweed (*Datura stramonium*), tree tobacco (*Nicotiana glauca*), *S. dubium*, black nightshade (*S. nigrum*), were reported as hosts of *T. absoluta*. Besides the Solanaceae, *T. absoluta* infests other wild plant species such as beetroot (*Beta vulgaris*), spinach (*Spinacia oleracea*), slender amaranth (*Amaranthus viridis*), Johnson grass (*Sorghum halepense*), and common cocklebur (*Xanthium strumarium*). *Chenopodium bonus-henricus*, *C. rubrum*, bindweed (*Convolvulus arvensis*) and common sowthistle (*Sonchus oleraceus*) (Desneux et al. 2010, Invasive Species Compendium, CABI 2017).

Worldwide, China has the largest growing areas and the highest yield of tomato and potato, accounting for 1/3 of the world tomato industry and 1/4 of the world potato industry (United Nations, FAO data, http://www.fao.org/faostat). The growing area and production of tomato in China increased rapidly since 2000. Until 2014, the tomato planting area reached more than 1 million hectares while the annual output of tomato reached 53.3 million tons (Fig. 1). Northwestern China, including Xinjiang, Neimenggu and Gansu provinces, is the main planting areas of tomato for export. Moreover, the Bohai Bay, including Liaoning, Hebei and Shandong, as well as Jiangsu and Henan provinces are also important tomato planting areas. For potatoes, the planting area was 5.6 million hectares, with a total output of up to 19 million tons in 2014 (China Rural Statistical Yearbook 2015, http://data.cnki.net). There are 8 of 32 provinces with an annual yield of more than 1 million tons, namely Yunnan, Sichuan, Chongqing, Guizhou, Gansu, Neimenggu, Heillongjiang and Shaanxi provinces (Fig. 2). Ministry of Agriculture (MOA) of China proposed the potato as the 4th staple food in 2016, which promoted the rapid development of the potato industry (Lu 2015). If *T. absoluta* is established in the above provinces, it will cause serious economic losses to the regional tomato and potato industry. China's potato planting acreage is expected to expand over 6.7 million acres by 2020. Most of the other cultivated and wild hosts can also be found in China. For example, eggplants are grown in most areas of China as one of the main vegetables in summer. *Solanum nigrum* (black nightshade) is native to China and exists throughout the mainland. These plants provide ideal hosts for the survival and colonization of *T. absoluta*.

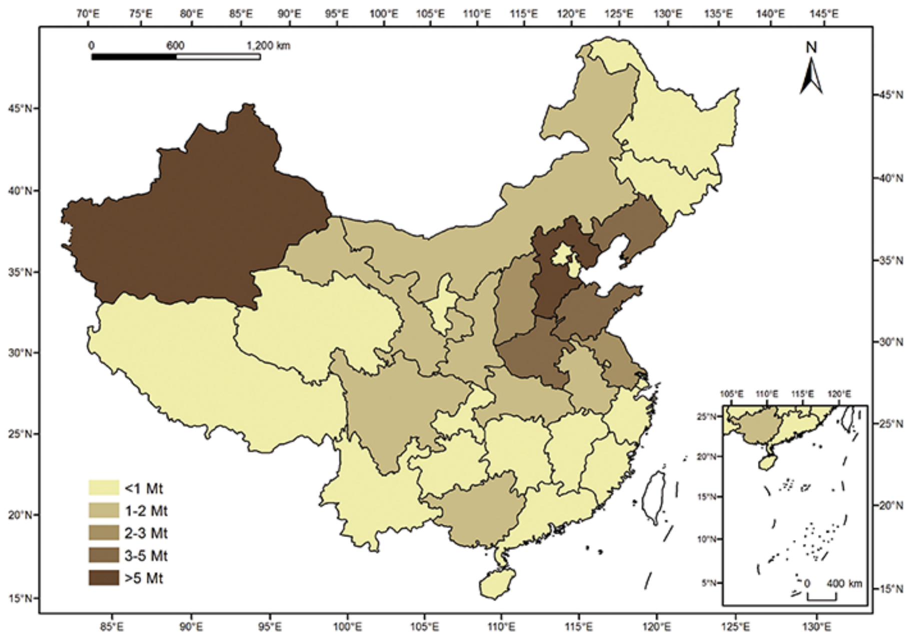

Fig. 1. Tomato production in mainland China.
Note: the data are from China Rural Statistical Yearbook 2011–2015 (http://data.cnki.net), Mt is the abbreviation of Million tons.

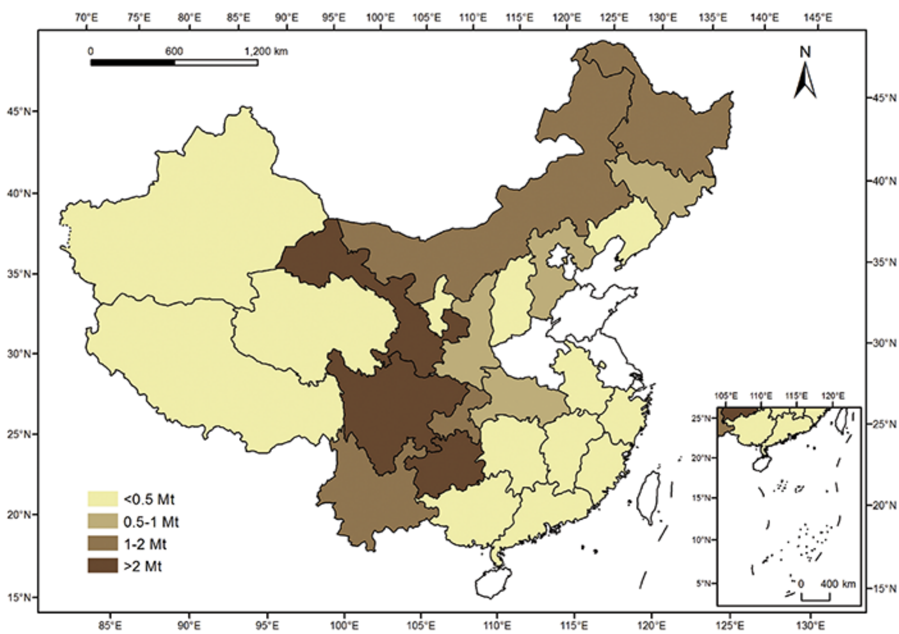

Fig. 2. Potato production in mainland China.
Note: the data are from China Rural Statistical Yearbook 2011–2015 (http://data.cnki.net), Mt is the abbreviation of Million tons.

Climatic suitability is the key abiotic factor determining the spread and establishment of a given invasive species. DYMEX 2.0 and ArcGIS 9.3 were used to predict the potential geographical distribution of *T. absoluta* in China. Both the standard meteorological dataset in DYMEX and monthly average climate data for 821 meteorological stations in China (1981–2010, from Chinese Meteorological Administration) were used in the model simulation. The initial value of parameters referred to the data proposed by Desneux et al. (2010). The DYMEX parameters were manually and iteratively adjusted until the potential geographical range as estimated by the EI values best coincided with the known distribution of *T. absoluta* in the native and invaded regions (525 locations of 72 countries). The parameters used in the DYMEX model are presented in Table 1. The predictive map suggested that the potential geographical distribution of *T. absoluta* in China covers most parts of Western, Central and Eastern China, while with few unsuitable areas in Xinjiang, Xizang and Qinghai (Fig. 3). The optimal potential area (high risk area) is mainly distributed in Yunnan, Western and Southeastern Guangxi, Southwestern Guangdong, and partly Western Hainan. Others were scattered in Southeastern Gansu, Middle Sichuan, Middle Shaanxi, and the junction of Henan and Shanxi. Central and East China represent the moderate risk.

Table 1. Parameters used in the DYMEX model for *T. absoluta*.

Parameter	Description	Modified value
DV0	Lower threshold temperature	8
DV1	Lower optimum temperature	20
DV2	Upper optimum temperature	25
DV3	Upper threshold temperature	35
SM0	Lower threshold of soil moisture	0.01
SM1	Lower limit of optimum soil moisture	0.1
SM2	Upper limit of optimum soil moisture	0.6
SM3	Upper threshold of soil moisture	1.8
PDD	Degree-days to complete one generation	460
TTCS	Cold stress temperature threshold	4
THCS	Cold stress accumulation rate	0
TTHS	Heat stress temperature threshold	41
THHS	Heat stress accumulation rate	0.0015
SMDS	Dry stress soil moisture threshold	0.001
HDS	Dry stress accumulation rate	−0.02
SMWS	Wet stress soil moisture threshold	2
HWS	Wet stress accumulation rate	0.002

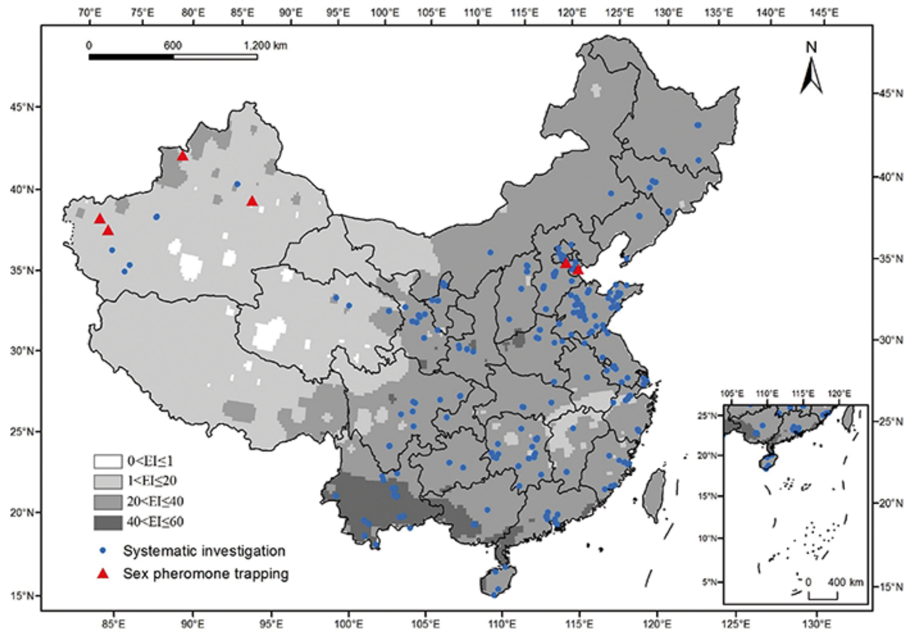

Fig. 3. Potential geographic distribution and tracking points of *T. absoluta* in mainland China. (0<EI≤1, no risk area; 1<EI≤20, low risk area; 20<EI≤40, middle risk area; 40<EI≤60, high risk area).

4 Quarantine & monitoring efforts

Quarantine-related measures against expansion have been extensively reported in previous literatures (Desneux et al. 2010, Campos et al. 2017). The invasion of *T. absoluta* into Europe (i.e. in Spain) from South America in 2016 has been notably attributed to the insufficient efforts of plant health inspection before their entry and movement within the European Community. Since then, the ineffective contingency measures adopted by plant protection agencies continued to result in a rapid expansion of this pest throughout Europe and even North Africa. *Tuta absoluta* are well-known to be readily introduced to new areas by means of fruits from invaded area. As a result, it has increased its range radius by 800 km per year in Afro-Eurasia countries, infesting almost 60% of the tomato cultivated land worldwide (Campos et al. 2017). More recently, the invasion and establishment of *T. absoluta* has resulted in yield loss of fresh tomato by 40% and an increase in tomato market price by 135% in Nigeria, which has been reported by the major media as a sensational social event. The rapid expansion and ineffective contingency should be ascribed to the missing joint-effort in quarantine and monitoring among countries throughout the Africa continent. In contrast, Department of Agriculture of the United States (a yet invaded country), has denominated this pest as a quarantine species with high invasion risk early since 2009. Federal orders were also issued to restrict or inhibit the entry of fruits as well as the *Solanum* sp., *Datura* spp. and *Nicotiana* spp., as potential host plants of *T. absoluta* from the infested countries (Bech et al. 2009, Desneux et al. 2010). Moreover, a monitoring network established in 2011 for timely detection of the presence of *T. absoluta* in the US appears successful in securing a rapid response once this pest has been detected.

In mainland China, the Centre for Management of Invasive Alien Species Ministry of Agriculture of the People's Republic of China (MOAPRC CMIAS) is responsible for post-border detection of alien species. In 2014, the Department of Biological Invasions (DBI), Institute of Plant Protection (IPP), Chinese Academy of Agricultural Sciences (CAAS) established a surveillance protocol for early detection of *T. absoluta* in potential suitable areas, including in 30 provinces in mainland China. The continuously detection of the pest based on sex pheromone traps (PH-937–1RR, Russell IPM, UK) was conducted in partial high-risk areas (Beijing, Tianjin, Hebei) and the nearest province to invaded countries (Xinjiang) (Fig. 3). These sex pheromone traps were checked once a week and replaced lures once a month. The systematic investigation by randomly sampling and checking on major host plant species (such as tomato, eggplant and night shade) of the pest in all the potential suitable areas (30 provinces) was also implemented (Fig. 3). The surveillance results showed no presence of *T. absoluta* in mainland China by the end of 2016. To prevent the pest spreading once it introduced, the National Agro-Tech Extension and Service Center (NATESC) will take charge to monitor this pest via the national monitoring network built by the participation of plant protection department of each province. Once it will detected, the contingency measures include rooting out and burning the infected plants, real-time monitoring by using intelligent monitoring system with sex pheromone, strict phytosanitary and area-wide joint prevention and control.

Nevertheless, following the saying "Don't open Pandora's box", the lessons from Western countries teach us that the best strategy is to make every effort to prevent this pest from entering China, among which quarantine is the key. Disappointedly, Ministry of Agriculture of the China P.R. has so far not included this pest species into the national quarantine list, despite that this species has not yet been detected in Entry-Exit Inspection and Quarantine Bureaus in China (http://www.pestchina.com 2016). We thus strongly call for strict and complete quarantine initiatives specifically targeting this pest species, as well as the further phytosanitary measures to minimize the risk of its invasion success. For instance, the imported tomato fruits and plant materials from the infested countries must be banned or subjected to methyl bromide fumigation, preferably in combination with irradiation treatment as a common quarantine practice (Hallman et al. 2013).

5 Potential control measures

Even though the pests have not invaded into China, we could learn more efficient IPM (Integrated Pest Management) solutions from the colonized countries (e.g. European countries) to build our own management system. Using environment friendly insecticides may help us to suppress the instant outbreak of the pest. In most South American countries, the chemical control method was used to control *T. absoluta.* The decision of chemical control for management of *T. absoluta* is based on adult captures in sexual pheromone trap (Benvenga et al. 2007). Organophosphates were initially used for *T. absoluta* control, which were gradually replaced by pyrethroids during the 1970s. With the development of insecticide, some novel insecticides were carried out to control this pest insect, such as avermectins, spinosad, tebufonozide, chlofenapyr and so on. However, *T. absoluta* has developed resistance against many insecticides since the use of chemical control tactics (Siqueira et al. 2000, 2001, Lietti et al. 2005, Campos et al. 2014, 2015, Roditakis et al. 2015). Thus, new environment friendly control methods (biological control, resistant plants and botanical insecticides) should be investigated and used in the future (Desneux et al. 2007, 2010, Guedes & Picanço, 2012).

Use of tomato variety resistance to *T. absoluta* may be an effective method to control the pest population while reducing pesticides use in integrated pest management programs (Maluf et al. 2010). The development of resistant tomato varieties has been intensively pursued since the early 1990s (Guedes & Picanço 2012, Sohrabi et al. 2016, 2017), and the leaf allelochemicals and trichome density have been considered as key tomato resistant features (De Oliveira et al. 2012). Glandular trichomes, particularly 2-tridecanone, zingiberene and acyl sugars have proved to be highly active against *T. absoluta* (Azevedo et al. 2003, Maluf et al. 2010, Terzidis et al. 2014). Some wild *Solanum* species have shown resistance/tolerance against *T. absoluta*, but it is difficult to transfer such traits into commercial tomato varieties due to species' incompatibility and/or risks of introducing undesirable characteristics (Oliveira et al. 2009, Terzidis et al. 2014). There has been no successful report of tomato hybrids resistant to *T. absoluta* and also no commercially-available tomato variety that has an acceptable degree of resistance to *T. absoluta* (Oliveira et al. 2009, Terzidis et al. 2014). The development of effective tomato varieties resistant to *T. absoluta* still remains in progress (Guedes & Picanço 2012).

Biological control, especially via releasing natural enemy arthropods, is one of the important solutions for sustainable suppression of the pest population boom up. The preventative experiments or programs using arthropod parasitoids or predators to suppress the *T. absoluta* have not yet been carried out in China. Most of the reported cases are only limited to laboratory tests. Since its arrival in the colonized countries, a set of endemic natural enemies have been reported on *T. absoluta*. In Brazil, some insect species or groups, *Xylocoris* sp., *Cycloneda sanguinea* and members of Phlaeothripidae, proved to be key predators of both egg and larval *T. absoluta* stages (Miranda et al. 1998). In addition, *Orius insidiosus* is reported to be an important predator of *T. absoluta* eggs and larvae in Venezuela and Iran (Salas 1995, Salehi et al. 2016). The green lacewing, *Chrysoperla externa* proved to be an ideal predator of *T. absoluta* larvae under laboratory conditions (Carneiro & Medeiros 1997). Some predator species have received attention as biological control agents for *T. absoluta*, eg the larvae, pupae and adults of *T. absoluta* were used to feed mite *Pyemotes* sp., that hint its potential use in biological control of the pest (Oliveira et al. 2007). The mirid bug *Macrolophus pygmeaus* has been proved to be an efficient predator for *T. absoluta*

(Bompard et al. 2013, Chailleux et al. 2013, Jaworski et al. 2013, Zappalà et al. 2013, Mollá et al. 2014). Except predatory natural enemies, a wide variety of parasitoids have been reported attacking egg, larval or pupal stages of *T. absoluta*. Some species of egg parasitoids belong to the families Encyrtidae (Colomo et al. 2002), Eupelmidae (Oatman & Platner 1989) and Trichogrammatidae (Colomo et al. 2002, Chailleux et al. 2012). Several parasitoid species from *Necremnus* order have occurred spontaneously in infested tomato fields in Spain (Mollá et al. 2008, Calvo et al. 2016, Naselli et al. 2017). In Southern Spain, the *Trichogramma achaeae* was used as potential natural enemy which showed highly efficient in decreasing *T. absoluta* infestation levels in tomato greenhouse (Cabello et al. 2009). The insect pathogen *Beauveria bassiana* can control many insects. However, their effect on *T. absoluta* is relatively poorly documented with regard to South America. Among the different entomopathogens that act against *T. absoluta*, *B. thuringiensis* var. *kurstaki* (Btk) may carry exceptional promise for use in Brazil (Giustolin et al. 2001). The inundative releases of potential natural enemies, such as *Encarsia formosa*, *Harmonia axyridis*, *Phytoseiulus persimilis*, *Trichogramma japonicum*, *T. dendrolimi* has been very successful in China.

While viewed as an environmentally benign approach, the introduction of exotic biological control agents may raise concern on the environmental risk such as Intraguild predation or non-target impacts in imported region (De Clercq et al. 2011). Importation biological control is considered because it could constitute a long-term sustainable management strategy for *T. absoluta*. For several *Trichogramma* species, mass-rearing programs have been set up and parasitoids are readily used in inundative biological control. Biological control of *T. absoluta* using *Trichogramma* is documented in Argentina (Riquelme & Botto 2003), Brazil (Parra & Zucchi 2004), Colombia (Vallejo 1999), and Chile (Estay & Bruna 2002). Using innudative releases of *T. exiguum* as part of a more comprehensive IPM strategy, parasitism levels reached 9.8–28.6% in open-field tomato in Colombia (Salas 2001).

6 Conclusion and future outlook

Since its first arrival in Europe a decade ago, the huge negative impacts on tomato industry due to *T. absoluta* invasion in Afro-Asian countries has entitled this species as a notorious and devastating pest worldwide. Given the aggressive nature of the pest and the ever-increasing commercial travel, it remains an enormous and constant threat with regard to the introduction of the tomato leaf miner into unaffected countries (Campos et al. 2017). As this pest is approaching the borders of the main tomato-producing countries, mainly China, Mexico and the United States, quarantine or monitoring initiatives have been launched to prevent the entry of this pest. In China, regulatory agencies and scientific community are currently seeking for a secure preventative package. Monitoring efforts play a key role in timely detection of *T. absoluta*. It is known that its arrival in invaded areas disrupted the established IPM system in local agriculture and consequently the extensive use of insecticides posed a major threat to human health and environment. Therefore, here we offer several recommendations against the potential invasion of this pest into China: (i) a prompt launch of quarantine program by our regulatory agencies are strongly recommended; (ii) greater fund support are expected to finance the build-up of a complete network allowing timely, flexible and accurate detection of this pest nationwide; (iii) researchers and extension specialists should develop preventative IPM packages to be fully prepared for fighting against the pest in case of its arrival. For the last aspect, while biocontrol programs by inundative release of parasitoids should be in a high priority status, other management options such as agricultural practices (e.g. manipulation of fertilization input) are suggested to be included into the package as well (Han et al. 2014, 2016). The sharing and further development of control approaches are of great relevance to the tomato production in both infested countries and the regions yet infested.

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References

Abdul-Rassoul, M.S. (2014): A New Host Record for Tomato Leaf Miner *Tuta absoluta* (Meyrick, 1917) in Baghdad Province, Iraq. – Bulletin of the Iraq Natural History Museum 13: 15–18.

Al-Jboory, I.J., Katbeh-Bader, A. & Shakir, A. (2012): First Observation and Identification of Some Natural Enemies Collected from Heavily Infested Tomato by *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Jordan. – Middle-East Journal of Scientific Research 11: 787–790.

Almatni, W. (2010): Tomato Leaf Miner *Tuta absoluta* Invades East Mediterranean Countries. – Arab and Near East Plant Protection Newsletter 50: 29.

Al-turaihi, E.H. (2014): The Impact of Newly Introduced Insect Tomato Borer (*Tuta absoluta*) on Environment and Agriculture in Qatar. – Qatar Foundation Annual Research Conference 2014, November 15–19, doi: 10.5339/qfarc.2014.EEPP0072, Doha, Qatar.

Azevedo, S.M., Ventura Faria, M., Maluf, W.R., Oliveira, A.C.B. & Freitas, J.A. (2003): Zingiberene-mediated Resistance to the South American Tomato Pinworm Derived from *Lycopersicon hirsutum* var. *hirsutum*. – Euphytica 134: 347–351.

Bajracharya, A.S.R., Mainali, R.P., Bhat, B., Bista, S., Shashank, P.R. & Meshram, N.M. (2016): The First Record of South American Tomato Leaf Miner, *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Nepal. – Journal of Entomology and Zoology Studies 4: 1359–1363.

Baniameri, V. & Cheraghian, A. (2012): The First Report and Control Strategies of *Tuta absoluta* in Iran. – EPPO Bulletin 42: 322–324.

Bawin, T., Dujeu, D., De Backer, L., Fauconnier, M., Lognay, G., Delaplace, P., Francis, F. & Verheggen, F.J. (2015): Could Alternative Solanaceous Hosts Act as Refuges for the Tomato Leafminer, *Tuta absoluta*? – Arthropod-Plant Interactions 9: 425–435.

Bawin, T., Dujeu, D., De Backer, L., Francis, F. & Verheggen, F.J. (2016): Ability of *Tuta absoluta* (Lepidoptera: Gelechiidae) to Develop on Alternative Host Plant Species. – Canadian Entomologist 148: 434–442.

Bech, R.A. (2009): Federal Order for Tomatoes from Countries where *Tuta absoluta* is Known to Occur. – Plant Protection and Quarantine, USDA-APHIS, 3 pp.

Benvenga, S.R., Fernandes, O.A. & Gravena, S. (2007): Decision Making for Integrated Pest Management of the South American Tomato Pinworm Based on Sexual Pheromone Traps. – Horticultura Brasileira 25: 164–169.

Bompard, A., Jaworski, C.C., Bearez, P. & Desneux, N. (2013): Sharing a Predator: Can an Invasive Alien Pest Affect the Predation on a Local Pest? – Population Ecology 55: 433–440.

Cabello, T., Gallego, J.R., Vila, E., Soler, A., Pino, M.D., Carnero, A., Hernández-Suárez, E. & Polaszek, A. (2009): Biological Control of the South American Tomato Pinworm. *Tuta absoluta* (Lep.:Gelechiidae), with Releases of *Trichogramma achaeae* (Hym.: Trichogrammatidae) in Tomato Greenhouses of Spain. – IOBC/WPRS Bulletin 49: 225–230.

Calvo, F., Soriano, J., Stansly, P. & Belda, J. (2016): Can the Parasitoid *Necremnus tutae* (Hymenoptera: Eulophidae) Improve Existing Biological Control of the Tomato leafminer *Tuta aboluta* (Lepidoptera: Gelechiidae)? – Bulletin of Entomological Research 106: 502–511.

Campos, M.R., Biondi, A., Adiga, A., Guedes, R.N.C & Desneux, N. (2017): From the Western Palaearctic Region to Beyond: *Tuta absoluta* 10 Years after Invading Europe. – Journal of Pest Science 90: 787–796.

Campos, M.R., Rodrigues, A.R.S., Silva, W.M., Silva, T.B.M., Silva, V.R.F., Guedes, R.N.C. & Siqueira, H.A.A. (2014): Spinosad and the Tomato Borer *Tuta absoluta*: a Bioinsecticide, an Invasive Pest Threat, and High Insecticide Resistance. – PLoS ONE 9: e103235, doi: 10.1371/journal.pone.0103235.

Campos, M.R., Silva, T.B.M., Silva, W.M., Silva, J.E. & Siqueira, H.A.A. (2015): Spinosyn Resistance in the Tomato Borer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). – Journal of Pest Science 88: 405–412.

Canadian Food Inspection Agency (2016): *Tuta absoluta* (Tomato Leafminer). – Fact Sheet, http://www.inspection.gc.ca/plants/plant-pests-invasive-species/insects/tomato-leafminer/fact-sheet/eng/1328634442933/1328887251933 , accessed May 2017.

Carneiro, J.R. & Medeiros, M.A. (1997): Potencial de Consumo de *Chrysoperla externa* (Neuroptera:Chrysopidae) *Utilizando ovos* de *Tuta absoluta* (Lepidoptera: Gelechiidae). – Abstracts of Congresso Brasileiro de Entomologia 16: 117–118, Salvador, Brazil.

Chailleux, A., Biondi, A., Han, P., Tabone, E. & Desneux, N. (2013): Suitability of the Host-plant System *Tuta absoluta*-Tomato for Trichogramma Parasitoids and Insights for Biological Control. – Journal of Economic Entomology 106: 2310–2321.

Chailleux, A., Desneux, N., Seguret, J., Do Thi Khanh, H., Maignet, P. & Tabone, E. (2012): Assessing European Egg Parasitoids as a Mean of Controlling the Invasive South American Tomato Pinworm *Tuta absoluta*. – PLoS ONE 7 (10): e48068, doi: 10.1371/journal.pone.0048068.

Colomo, M.V., Berta, D.C. & Chocobar, M.J. (2002): El Complejo de Himenópteros Parasitoides que Atacan a la "Polilla del Tomate" *Tuta absoluta* (Lepidoptera: Gelechiidae) en la Argentina. – Acta Zoologica Lilloana 46: 81–92.

De Clercq, P., Mason, P.G. & Babendreier, D. (2011): Benefits and Risks of Exotic Biological Control Agents. – Biocontrol 56: 681–698.

De Oliveira, C.M., De Andrade Júnior, V.C., Maluf, W.R., Neiva, I.P. & Maciel, G.M. (2012): Resistance of Tomato strains to the Moth *Tuta absoluta* Imparted by Allelochemicals and Trichome Density. – Ciência e Agrotecnologia 36: 45–52.

Desneux, N., Decourtye, A. & Delpuech, J. (2007): The Sublethal Effects of Pesticides on Beneficial Arthropods. – Annual Review of Entomology 52: 81–106.

Desneux, N., Luna, M.G., Guillemaud, T. & Urbaneja, A. (2011): The Invasive South American Tomato Pinworm, *Tuta absoluta*, Continues to Spread in Afro-Eurasia and beyond: the New Threat to Tomato World Production. – Journal of Pest Science 84: 403–408.

Desneux, N., Wajnberg, E., Wyckhuys, K.A.G., Burgio, G., Arpaia, S., Narváez-Vasquez, C.A., González-Cabrera, J., Ruescas, D.C., Tabone, E., Frandon, J., Pizzol, J., Poncet, C., Cabello, T. & Urbaneja, A. (2010): Biological Invasion of European Tomato Crops by *Tuta absoluta*: Ecology, Geographic Expansion and Prospects for Biological Control. – Journal of Pest Science 83: 197–215.

Estay, P. & Bruna, A. (2002): Insectos y Ácaros Asociados al Tomate en Chile. – In: Estay P. & Bruna, A. (eds.): Insectos, Ácaros y Enfermedadesasociados al Tomate en Chile. – Centro Regional de Investigación INIA La Platina, 9–22, Santiago, Chile.

Ferracini, C., Ingegno, B.L., Navone, P., Ferrari, E., Mosti, M., Tavella, L. & Alma, A. (2012): Adaptation of Indigenous Larval Parasitoids to *Tuta absoluta* (Lepidoptera: Gelechiidae) in Italy. – Journal of Economic Entomology 105: 1311–1319.

Galdino, T.V.S., Picanço, M.C., Ferreira, D.O., Silva, G.A.R., Souza, T.C. & Silva, G.A. (2015): Is the Performance of a Specialist Herbivore Affected by Female Choices and the Adaptability of the Offspring? – PLoS ONE 11: e0143389, doi: 10.1371/journal.pone.0143389.

Giustolin, T.A., Vendramim, J.D., Alves, S.B. & Vieira, S.A. (2001): Susceptibility of *Tuta absoluta* (Meyrick) (Lep, Gelechiidae) Reared on Two Species of Lycopersicon to *Bacillus thuringiensis* var. kurstaki. – Journal of Applied Entomology 125: 551–556.

Guedes, R.N.C. & Picanço, M.C. (2012): The Tomato Borer *Tuta absoluta* in South America: Pest status, Management and Insecticide Resistance. – Bulletin OEPP/EPPO Bulletin 42: 211–216.

Hallman, G.J., Arthur, V., Blackburn, C.M. & Parker, A.G. (2013): The Case for a Generic Phytosanitary Irradiation Dose of 250 Gy for Lepidoptera Eggs and Larvae. – Radiation Physics and Chemistry 89: 70–75.

Han, P., Desneux, N., Amiens-Desneux, E., Le Bot, J., Bearez, P. & Lavoir, A.V. (2016): Does Plant Cultivar Difference Modify the Bottom-up Effects of Resource Limitation on Plant-herbivorous Insect Interactions? – Journal of Chemical Ecology 42: 1293–1303.

Han, P., Lavoir, A.V., Le Bot, J., Amiens-Desneux, E. & Desneux, N. (2014): Nitrogen and Water Availability to Tomato Plants Triggers Bottom-up Effects on the Leafminer *Tuta absoluta*. – Scientific Reports 4: 4455, doi: 10.1038/srep04455.

Hossain, M.S., Mian, M.Y. & Muniappan, R. (2016): First Record of *Tuta absoluta* (Lepidoptera: Gelechiidae) from Bangladesh. – Journal of Agricultural and Urban Entomology 32: 101–105.

Ibrahim, M.Y., Mehrez, E.A., Edrees, M.S., Aodie, B.I. & Al-Masrey, A.R. (2012): The First Record to Tomato Leaf miner, *Tuta absoluta* (Povolny) (Lepidoptera: Gelechiidae) at Homs Governorate, Syria. – Persian Gulf Crop Protection 1: 53–63.

Invasive Species Compendium, CABI (2017): *Tuta absoluta* (Tomato Leafminer). – http://www.cabi.org/isc/datasheet/49260 , accessed May 2017.

Jaworski, C.C., Bompard, A., Genies, L., Amiens-Desneux, E. & Desneux, N. (2013): Preference and Prey Switching in a Generalist Predator Attacking Local and Invasive Alien Pests. – PLoS ONE 8: e82231, doi: 10.1371/journal.pone.0082231.

Kılıç, T. (2010): First Record of *Tuta absoluta* in Turkey. – Phytoparasitica 38: 243.

Lietti, M.M.M., Botto, E. & Alzogaray, R.A. (2005): Insecticide Resistance in Argentine Populations of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). – Neotropical Entomology 34: 113–119.

Lu, X.P. (2015): Strategy of Potato as Staple food: Significance, Bottlenecks and Policy Suggestions. – Journal of Huazhong Agricultural University (Social Sciences Edition) 3: 1–7.

Maluf, W.R., Silva, V.F., Cardoso, M.D.G., Gomes, L.A.A., Neto, A.C.G., Maciel, G.M. & Nízio, D.A.C. (2010): Resistance to the South American Tomato Pinworm *Tuta absoluta* in High Acylsugar and/or High Zingiberene Tomato Genotypes. – Euphytica 176: 113–123.

Miranda, M.M.M., Picanco, M., Zanuncio, J.C. & Guedes, R.N.C. (1998): Ecological Life Table of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). – Biocontrol Science and Technology 8: 597–606.

Mollá, O., Biondi, A., Alonso-Valiente, M. & Urbaneja, A. (2014): A Comparative Life History Study of Two Mirid Bugs Preying on *Tuta absoluta* and *Ephestia kuehniella* Eggs on Tomato Crops: Implications for Biological Control. – Biocontrol 59: 175–183.

Mollá, O., Montón, H., Crespo, F.J.B. & García, A.U. (2008): La Polilla del Tomate *Tuta absoluta* (Meyrick), una Nueva Plaga Invasora. – Terralia 69: 36–42.

Naselli, M., Biondi, A., Garzia, G.P., Desneux, N., Russo, A., Siscaro, G. & Zappalà, L. (2017): Insights into Food Webs Associated with the South American Tomato Pinworm. – Pest Management Science, doi: 10.1002/ps.4562.

Oatman, E.R. & Platner, G.R. (1989): Parasites of the Potato Tuberworm, Tomato Pinworm and Other Closely Related Gelechiids. – Proceedings of the Hawaiian Entomological Society 29: 23–30.

Oliveira, C.R.F., Matos, C.H.C. & Hatano, E. (2007): Occurrence of *Pyemotes* sp. on *Tuta absoluta* (Meyrick). – Brazilian Archives of Biology and Technology 50: 929–932.

Oliveira, F.A., Silva, D.J.H., Leite, G.L.D., Jham, G.N. & Picanço, M. (2009): Resistance of 57 Greenhouse-grown Accessions of *Lycopersicon esculentum* and Three Cultivars to *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). – Scientia Horticulturae 119: 182–187.

Parra, J.R.P. & Zucchi, R.A. (2004): *Trichogramma* in Brazil: Feasibility of Use after Twenty Years of Research. – Neotropical Entomology 33: 271–281.

Riquelme, M.B. & Botto, E.N. (2003): Dispersión y persistencia de *Trichogrammatoidea bactrae* (Hymenoptera: Trichogrammatidae) en Cultivo de Tomate Bajo Cubierta. – Resúmenes XXV Cong. Chil. De Entomol., 23, Talca, Chile.

Roditakis, E., Vasakis, E., Grispou, M., Stavrakaki, M., Nauen, R., Gravouil, M. & Bassi, A. (2015): First Report of *Tuta absoluta* Resistance to Diamide Insecticides. – Journal of Pest Science 88: 9–16.

Roques, A., Auger-Rozenberg, M.A., Blackburn, T.M., Garnas, J., Pyšek, P., Rabitsch, W., Richardson, D.M., Wingfield, M.J., Liebhold, A.M. & Duncan, R.P. (2016): Temporal and interspecific variation in rates of spread for insect species invading Europe during the last 200 years. – Biological Invasions 18: 907–920.

Salas, J. (1995): *Orius insidiosus* (Hemiptera: Anthocoridae) Supresencia en la Region Centro Occidental de Venezuela. – Agron Trop 45: 637–645.

Salas, J. (2001): Insectos Plagas del Tomate. Manejo Integrado. Maracay, Ven., Instituto Nacional de Investigaciones Agrícolas. – Centro de Investigaciones Agropecuarias del Estado Lara (Serie B–No. 1), 102.

Salehi, Z., Yarahmadi, F., Rasekh, A. & Sohani, N.Z. (2016): Functional Responses of *Orius albidipennis* Reuter (Hemiptera, Anthocoridae) to *Tuta absoluta* Meyrick (Lepidoptera, Gelechiidae) on Two Tomato Cultivars with Different Leaf Morphological Characteristics. – Entomologia Generalis 36: 127–136.

Seplyarsky, V., Weiss, M. & Haberman, A. (2010): *Tuta absoluta* Povolny (Lepidoptera: Gelechiidae), a New Invasive Species in Israel. – Phytoparasitica 38: 445.

Siqueira, H.A.A., Guedes, R.N.C. & Picanço, M.C. (2000): Insecticide Resistance in Populations of *Tuta absoluta* (Lepidoptera: Gelechiidae). – Agricultural and Forest Entomology 2: 147–153.

Siqueira, H.A.A., Guedes, R.N.C., Fragoso, D.B. & Magalhaes, L.C. (2001): Abamectin Resistance and Synergism in Brazilian Populations of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). – International Journal of Pest Management 47: 247–251.

Sohrabi, F., Nooryazdan, H.R., Gharati, B. & Saeidi, Z. (2016): Evaluation of Ten Tomato Cultivars for Resistance against Tomato Leaf Miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under Field Infestation Conditions. – Entomologia Generalis 36: 163–175.

Sohrabi, F., Nooryazdan, H.R., Gharati, B. & Saeidi, Z. (2017): Plant Resistance to the Moth *Tuta absoluta* (Meyrick) (Lepidoptera:Gelechiidae) in Tomato Cultivars. – Neotropical Entomology 46: 203–209.

Sridhar, V., Chakravarthy, A.K., Asokan, R., Vinesh, L.S., Rebijith, K.B. & Vennila, S. (2014): New Record of the Invasive South American Tomato Leaf Miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in India. – Pest Management in Horticultural Ecosystems 20: 148–154.

Terzidis, A.N., Wilcockson, S. & Leifert, C. (2014): The Tomato Leaf Miner (Tuta absoluta): Conventional Pest problem, Organic Management Solutions? – Organic Agriculture 4: 43–61.

Tonnang, H.E.Z., Mohamed, S.F., Khamis, F. & Ekesi, S. (2015): Identification and Risk Assessment for Worldwide Invasion and Spread of *Tuta absoluta* with a Focus on Sub-Saharan Africa: Implications for Phytosanitary Measures and Management. – PLoS ONE 10: 1–19, doi: 10.1371/journal.pone.0135283.

Torres, J. B., Faria, C.A., Evangelista, W.S. & Pratissoli, D. (2001): Within Plant Distribution of Leaf Miner *Tuta absoluta* (Meyrick) Immatures in Processing Tomatoes, with Notes on Plant Phenology. – International Journal of Pest Management 47 (3): 173–178.

Vallejo, F.A. (1999): Mejoramiento Genético y Producción de Tomate en Colombia. – Universidad Nacional de Colombia, 216.

Zappalà, L., Biondi, A., Alma, A., Al-Jboory, I.J., Arnò, J., Bayram, A., Chailleux, A., El-Arnaouty, A., Gerling, D., Guenaoui, Y., Shaltiel-Harpaz, L., Siscaro, G., Stavrinides, M., Tavella, L., Aznar, R.V., Urbaneja, A. & Desneux, N. (2013): Natural Enemies of the South American Moth, *Tuta absoluta*, in Europe, North Africa and Middle East, and Their Potential Use in Pest Control Strategies. – Journal of Pest Science 86: 635–647.

Zou, J.L., Liu, C.L., Yin, G.Q. & Tang, Z.P. (2015): Spatial Patterns and Economic Effects of China's Trade with Countries along the Belt and Road. – Progress in Geography 34: 598–605.

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