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Occurrence, biology, natural enemies and management of *Tuta absoluta* in Africa

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With 1 figure and 1 table

Abstract: The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is a devastating invasive pest of tomato crops in several areas around the world including Africa. Here, we comprehensively review and discuss the relevant scientific knowledge on its occurrence, biological and ecological aspects, fortuitous insect natural enemies, and potential advantages and constraints of pest management scenarios adopted against this pest in tomato crops in both Northern and Sub-Saharan Africa. We conclude the manuscript with a comprehensive research agenda providing future priorities towards sustainable control of this important tomato pest.

Keywords: augmentative biological control, classical biological control, conservative biological control, Gelechiidae, invasive pest, Integrated Pest Management, South American tomato pinworm

1 Introduction

Invasive alien insects are generally characterized by successful adaptations to newly invaded areas (Pimentel et al. 2005, Asplen et al. 2015). Some of them are serious threats to agricultural crops, biodiversity and ecosystem functioning, resulting in major economic losses and ecological damages (Pimentel et al. 2000, Sala et al. 2000, Simberloff et al. 2013). Among invasive insects of economic importance, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), a leafminer native to South America (Guedes & Picanço 2012, Campos et al. 2017, Biondi et al. 2018), is considered a key, devastating pest of processing and fresh tomatoes (*Solanum lycopersicum* L.). This pest was first detected outside South America in 2006 and it is now distributed in most tomato-growing areas in Europe, Africa and Asia (Desneux et al. 2010, 2011, Brévault et al. 2014, Biondi et al. 2018, Han et al. 2018). However, this pest has not been reported in China that is the largest tomato producing country worldwide (Xian et al. 2017, Han et al. 2018).

This Neotropical insect has reached economic pest status in most invaded areas around the world because of its high demographical potential, which is mainly due to a short generation time, a relatively wide host range, a good thermal adaptability and its aptitude to develop insecticide resistance (Desneux et al. 2010, Guedes & Picanço 2012, Tropea Garzia et al. 2012, Biondi et al. 2018). Factors including temperature, predation, parasitism, egg viability, and entomopathogenic agents were proven to affect natural development and survival of this pest (Tonnag et al. 2015, Guimapi et al. 2016, Martins et al. 2016, Bacci et al. 2018). The four larval stages feed on leaves, stems, twigs and fruits, which can cause substantial crop damages and yield losses reaching 100% on tomato crops growing under greenhouse and/or open-field conditions (Desneux et al. 2010, 2011, Biondi et al. 2018). In this perspective, developing and implementing the most appropriate control tactics against this pest is considered a priority for achieving successful and sustainable management of *T. absoluta* worldwide (Campos et al. 2017, Biondi et al. 2018). In Africa, *T. absoluta* has spread rapidly since its first arrival in three North African countries (Tunisia, Algeria and Morocco), during the 2007–2008 tomato growing season. It is now a well-established major economic pest in both Northern and Sub-Saharan Africa (Desneux et al. 2010, Brévault et al. 2014, Tonnang et al. 2015, Mutamiswa et al. 2017). For this reason and with the aim to find out the most suitable management tactics against this pest, several field surveys and various research activities have been performed in several African countries. Here, we review the most relevant literature on the geographical distribution, the field bio-ecology, the natural enemies and all categories of pest management approaches adopted against *T. absoluta* in Africa. We conclude the manuscript by listing the potential future research priorities with the aim of improving the exploitation of local resources for the sustainable management of this global agroecological and economic problem.

2 Predicting the extent of spread through modeling

In Tonnang et al. (2015), molecular characterization of specimens and geo-reference of occurrence records of *T. absoluta* were combined with biological and ecological data into a CLIMEX model to predict the environmental suitability and potential spread of the pest, with focus to Eastern Africa. Results revealed that factors such as temperature and moisture characterized *T. absoluta* population growth. While, the pest ability to survive the cold, hot, wet and dry stress environment are key factors, which delineate its range. Africa was portrayed to be at high risk of invasion and establishment of the pest. A subsequent study proposed a model to predict the timing of spread of *T. absoluta* invasion across Africa (Guimapi et al. 2016). Using rules based on cellular automata approach, the authors determined, among a number of variables (vegetation, temperature, relative humidity, and area of tomato production), that relative humidity seems to have the strongest influence in enhancing the spread of *T. absoluta* by determining the choice of a location during its invasion and spread (Guimapi et al. 2016). These authors indicated that, in all simulations, when relative humidity is included as parameter, invasion and spread evolution of *T. absoluta* are the closest to the boundaries of natural observations. Simulations by inferring *T. absoluta* natural aptitude to fly long distances demonstrated that the pest was capable of expanding its distribution range to the Republic of South of Africa 10 years after first records in Spain (2006). The projections became validated, as by 2016 *T. absoluta* was reported in the Republic of South Africa (DAFF 2016).

3 Occurrence, ecology and damage

Currently, *T. absoluta* is reported in 41 of the 54 African countries (Fig. 1). However, only in the reports for 22 countries the date of first record of *T. absoluta* was indicated. No further information regarding the year of the first record and/or the

Fig. 1. Occurrence and years of first report of *Tuta absoluta* invasion in Africa, as of August 2018, based on the published literature. Years of first report are indicated as follows: 08 (2008), 09 (2009), 10 (2010), 12 (2012), 13 (2013), 14 (2014), 15 (2015), 16 (2017), 17 (2017).

presence of the pest is available for 32 countries (Fig. 1). The pest probably moved from Northern Africa to Eastern Africa through Sudan, and then spread throughout Sub-Saharan Africa, though this hypothesis is yet to be proved. Below we provide the available information on the spread, host range and field ecology of *T. absoluta* in those countries where the pest has been studied and for which published data are available.

3.1 Northern Africa

Tuta absoluta was first reported in the African continent in three countries of the Maghreb area (Tunisia, Algeria, and Morocco) during the year 2008 before being found in Libya and Egypt in 2009 (EPPO 2008, 2009, 2011, Guenaoui 2008, Moussa et al. 2013, Salama et al. 2015) (Fig. 1). In Tunisia, *T. absoluta* was first detected in October 2008 in open-field tomato crops in the Governorate of Sousse, Center-East region (EPPO 2009, Cherif et al. 2013). Since then, it quickly spread to all tomato-producing areas. Pheromone-based monitoring and sampling of tomato leaves in northeastern Tunisia during the spring-summer growing season (March – July) showed that *T. absoluta* can have 4 to 5 male flight peaks with higher activity reported in summer during which the monthly temperatures averaged 25–30 °C, while three generations were recorded for eggs and larvae (Cherif & Grissa-Lebdi 2017). However, during the period November – May, *T. absoluta* can have 4 generations on tomatoes under greenhouse conditions of northeastern Tunisia (Grissa-Lebdi et al. 2011). In the same region, three flight peaks of *T. absoluta* males were recorded between January and May in greenhouses, with the highest trap counts recorded in spring (Cherif et al. 2013). In Tunisia, *T. absoluta* can be found on either potato (*Solanum tuberosum* L.), eggplant (*S. melongena* L.) or tomato (mainly), while this pest has a shorter development time on tomato compared to the two other host plants (Cherif et al. 2018d).

In Algeria, *T. absoluta* was first detected in Mostaganem (Northwest) in March 2008 (Guenaoui 2008) before spreading to other tomato-producing areas. In this country, *T. absoluta* can attack a wide range of host plants, in addition to tomato, which are: (i) the Solanaceae (*Solanum elaeagnifolium* Cavanilles, *Solanum nigrum* L., *Datura stramonium* L., *Solanum tuberosum* L., and *Solanum melongena* L.), (ii) the Amaranthaceae (*Chenopodium rubrum* L., *Chenopodium bonus-henricus* L., *Spinacia oleracea* L., and *Beta vulgaris* L.), and (iii) the Fabaceae (*Phaseolus vulgaris* L.) (Drouai et al. 2016). In a tomato greenhouse in northeastern Algeria, it was shown that *T. absoluta* had three generations within a short period, with the first male flight detected in mid-December and the highest densities of all life stages were recorded between mid-March and the end of the crop season, taking into account that during the period December – March, greenhouse temperatures were between 19 and 27 °C (Allache et al. 2012). However, in another greenhouse located in the same region, *T. absoluta* had six generations during the tomato growing season extending from October to May, with the highest numbers of immature stages being reported in mid-April (Allache et al. 2015). Monitoring using pheromone-baited traps showed that the occurrence and densities of *T. absoluta* eggs and larvae on tomato plants depended on both temperature and tomato cultivars grown in greenhouses of Biskra region in northeastern Algeria (Allache et al. 2017).

Tomato crop cultivation constitutes the major horticultural sector in Morocco in terms of planted areas and total production and exports in tons. In this country, *T. absoluta* was first found in the northern coastal (Mediterranean) region of Nador in April 2008, infesting open-field tomatoes (Ouardi et al. 2012). During the growing season 2008–2009, *T. absoluta* has spread rapidly to occur in all Moroccan tomato-producing regions causing damage up to 100% in some processing tomato fields

(Ouardi 2011, Ait Taadaouit et al. 2012, Attrassi 2015). In addition to tomatoes, *T. absoluta* is also infesting potatoes in Morocco (Ouardi 2011). Monitoring based on pheromone traps revealed the presence of the pest year-round at high to very high frequency (Ouardi et al. 2012).

In Egypt, *T. absoluta* was first detected in 2009 in tomatoes in Marsa Matrouh (northwestern Egypt), then the pest rapidly spread to the upper and lower regions of Egypt (Moussa et al. 2013, Salama et al. 2015). In several Egyptian tomato-producing areas, the degree of damage by this insect even reached 100% (Moussa et al. 2013). Under plastic greenhouse conditions in Nasr city (Cairo area, northern Egypt), infestation began in the third week of March and both the highest numbers of *T. absoluta* larvae and percentage of tomato infestation occurred in July (Ata & Megahed 2014). These authors found that *T. absoluta* had four generations on tomato from March to July with mean daily temperatures extended from 19 °C in mid-March to 28 °C in early July. In another study, carried out in open-field tomatoes in Assiut region (Upper Egypt) it was shown that *T. absoluta* can have 13 generations per year (Mohamed 2011).

3.2 Eastern Africa

The spread of *T. absoluta* from Northern to Eastern Africa seems to have transited through Sudan (Fig. 1). In Sudan, the pest was first detected in a tomato greenhouse around Khartoum in 2010, and within less than two years the pest has spread to all tomato-growing regions of North, West and Central Sudan. The pest has also swiftly moved southwards, where it had been reported from southern Kordofan, on the border with the Republic of South Sudan. Fruit damage was reported to range between 80 and 100% in most open-field tomato crops in Khartoum State. In addition to tomato, up to 50% *T. absoluta* damage was observed on potato foliage at Western Umdurman Agricultural Scheme and Karery in Khartoum State (Mohamed et al. 2012). Between 2011 and 2014, a wide survey using pheromone traps was carried out in five regions in Sudan to establish the host plants of *T. absoluta*. The results revealed that the principal host plant was tomato, but also this pest attacked potato, eggplant, Jimson weed (*Datura stramonium* L.) and *S. dubium* Fresen in the family Solanaceae, and broad bean (*Vicia faba* L.) and alfalfa plant (*Medicago sativa* L.) in the family Fabaceae (Mohamed et al. 2015). It is believed that from Sudan, *T. absoluta* migrated to Kenya via Ethiopia.

Tuta absoluta was reported to have traversed into Ethiopia via Sudan in 2012 (Goftishu et al. 2014, Retta & Berhe 2015). Similarly to other countries, widespread surveys were conducted in greenhouse and open-field on tomato crops using pheromone traps and the results confirmed the presence of the pest (Goftishu et al. 2014). According to the same authors, heavy losses in tomato crops were reported in greenhouses in eastern Ethiopia where young tomato plants died before flowering due to heavy infestation by *T. absoluta*. In Kenya, *T. absoluta* was first detected in mid March 2014 in Mpeketoni and Witu, in coastal Kenya, and later in Isiolo and Kirinyaga, in open-field tomatoes by the International Centre of Insect Physiology and Ecology (ICIPE) and by personnel of the Kenya Plant Health Inspectorate Service (KEPHIS), and officially reported in June of the same year (IPPC 2014). It is believed that the pest expanded its ranges to Kenya through Isiolo that is considered as a gateway town in the Kenya – Ethiopia transit corridor. From Kenya, the pest invaded Tanzania (2014), Uganda (2015) and other countries of the region respectively (Chidege et al. 2016, Tumuhaise et al. 2016, Anonymous 2018).

3.3 Western Africa

In Western Africa, *T. absoluta* was officially first detected in Senegal in 2012 (Pfeiffer et al. 2013, Brévault et al. 2014), then in 2013 in Niger and Cape Verde (Duarte 2013, Adamou et al. 2016), in 2016 in Nigeria and Burkina Faso (EPPO 2016, Borisade et al. 2017, Son et al. 2017), and in 2017 in Ghana (IPPC 2017a) (Fig. 1). However, *T. absoluta* has been thought to be present in most other West African countries including, for example, Benin, Cameroon, Guinea, Ivory Coast, Mali and Togo (USDA 2011, El-Lissy 2014, FAO 2018) (Fig. 1).

In Senegal, a preliminary field survey in the main vegetable-producing area (Niayes) reported that tomato fields were abandoned by farmers during February – May 2013 crop cycle, due to severe damages induced by *T. absoluta* larvae (Brévault et al. 2014). Two years after its first report (Pfeiffer et al. 2013), the pest was reported throughout the country, but mainly on the coastal part where resource availability (almost continuous tomato production for fresh market) and more temperate climate are favorable (Sylla et al. 2017). Adult moths were trapped in some areas in Senegal with very few tomato plants, suggesting that moth populations are extremely mobile or are able to persist on alternative host plants. Larvae were recovered from other solanaceous crops in this country such as potato, eggplant, Ethiopian eggplant (*Solanum aethiopicum* L.), whereas other solanaceous plants, such as pepper and sweet pepper, were consistently less infested (Brévault et al. 2014, Sylla, S., unpublished data). Field monitoring throughout the year in the most infested area in Senegal (Niayes) showed highest incidence of *T. absoluta* populations over the late dry season, from April to June, followed by a significant decline during the rainy season, from July to September (Brévault et al. 2014, Sylla et al. 2017). The decrease of resource availability in the surrounding landscape of monitored fields, especially tomato crops, was the main factor affecting the population dynamics over the rainy season. However, alternative host crops such as eggplant and Ethiopian eggplant can provide reservoirs for residual populations of the pest (Sylla et al. 2018).

Three years after initial detection of *T. absoluta* in Niger, more specifically in Burburkabé and Talkoboye (15 and 70 km from Niamey) a national survey showed that the pest has spread to and established in 7 of the 8 regions of Niger (Adamou et al. 2017). In Nigeria, the largest tomato producer in Sub-Saharan Africa (FAOSTAT 2016), *T. absoluta* was first detected in Daura, Katsina State (northern Nigeria) in April 2015. It was later reported in Kano State in June 2015 and Abeokuta, Ogun State in September 2015 and has since spread to all the other tomato-producing States (Oke et al. 2016, 2017a). *Tuta absoluta* monitoring using water-light traps showed very high pest densities with trap catches up to 4.872 adults per trap per day (Oke et al. 2017a). These authors indicated that such invasion led to a national destruction of tomato farms, which resulted in the shutdown of Dangote tomato processing industry which was slated to start production in 2015. *Tuta absoluta* caused over 80% loss of tomato production in Nigeria in the first cycle of the season 2016 as consequence of a sporadic attack by this insect in northern parts of the country where the pest has been much restricted (Borisade et al. 2017). Tomato yield losses due to *T. absoluta* invasion and spread in Nigeria is equivalent to 720.000 metric tons, taking into account that the country currently produces 1.8 million tons of tomatoes annually (Sanda et al. 2018). In Cameroon, three regions (Northeast, West and South) were reportedly affected by *T. absoluta* with severe yield losses reaching 100% (FAO 2018).

3.4 Southern and Central Africa

Tuta absoluta is currently established throughout Southern Africa except in Madagascar and Mauritius, while in Central Africa, this pest is present in Democratic Republic of the Congo, Equatorial Guinea, Rwanda and Sao Tome and Principe (FAO 2015, 2018, Luangala et al. 2016, Chidege et al. 2017, IPPC 2017b, 2017c, Mutamiswa et al. 2017, Visser et al. 2017, EPPO 2018) (Fig. 1). *Tuta absoluta* was first recorded in South Africa during August 2016 from synthetic sex pheromone traps in Mpumalanga province set up along the border with Mozambique (DAFF 2016). By May 2017, the pest had invaded open-field and greenhouse tomato crops in all nine provinces of South Africa (DAFF 2017). Following *T. absoluta* invasion, countries that did not have this pest at that time banned tomato (and other Solanaceae crops) imports from South Africa. The impact of this ban on the tomato export market has not been estimated yet. Likewise, the impact of *T. absoluta* on national production of tomatoes is yet to be estimated (Modiselle et al. 2017).

As predicted by Tonnang et al. (2015), *T. absoluta* is a persistent pest in Limpopo and Mpumalanga provinces of South Africa where tomatoes are grown largely under irrigation in open-fields due to favorable weather year-round. Despite the continuous presence of *T. absoluta*, a clear pattern has emerged whereby commercial farmers with access to various classes of registered insecticides are better able to manage *T. absoluta* infestations. The pest is devastating fields of organic and resource-poor smallholder farmers where 50 – 100% crop losses are recorded (Nofemela, R., unpublished data). These losses have a significant impact on household food security, as the profits are used to fund other needs. Likewise, the economic impact of *T. absoluta* on potato production has not been determined in South Africa; all we know at this moment is that high numbers of this pest are recorded in pheromone traps on potato fields and that feeding is limited to foliage (Visser, D., ARC-VOPI, personal communication). In addition, its impact on production of host plants such as pepper and eggplant is still unknown.

In Botswana, *T. absoluta* was first found in a tomato field in the Northeast district in December 2016 (Mutamiswa et al. 2017). In the following year, it was trapped in most regions of the country, both in host crops and wild habitats. Interestingly, *T. absoluta* was detected in areas, such as Moremi Island (Okavango Delta), more than 200 km from the nearest human settlements and agricultural activities (Machekano et al. 2018). In this country, the three wild host plants *Solanum coccineum* (Jacq.),

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Solanum supinum (Dunal), and *Solanum aculeatissimum* (Jacq.) were reported, in addition to other abiotic factors (e.g., climate suitability and high thermal tolerance), as major dispersal drivers leading to successful establishment of *T. absoluta* in Botswana (Machekano et al. 2018).

In Zambia, field surveys conducted in 2016 using pheromone delta traps showed that *T. absoluta* is present in 12 districts located in either Northern, Muchinga, Copperbelt, Lusaka, Central or Southern Provinces, with the highest infestation levels reported in the Central province (Luangala et al. 2016). This study showed that some of the surveyed farms in Zambia were highly infested with about 90% of crop damage, and that yields were reduced to zero by the end of the third week of infestation where no insecticide treatments were applied. In 2018, surveys in Zambia showed that, in most cases, farmers had learnt how to control *T. absoluta* on tomato but weekly insecticide treatments were needed (Kenis M., unpublished data). In southwestern Angola (Namibe Province), percent damage of open-field tomato crops induced by *T. absoluta* ranged from 84% to 100% where approximately 256 ha out of 3.500.00 ha under cultivation in 2017 were completely destroyed (Chidege et al. 2017). Knowledge of the damaging potential of this pest in other South and Central African countries is still missing. However, the field scenario could not be much different than the one observed in the other tropical African countries.

4 Fortuitous natural enemies

Since the arrival of *T. absoluta* in Africa, several studies were carried out to assess which indigenous natural enemies are able to attack the invasive pest and could

Table 1. Current knowledge of fortuitous natural enemies associated with, or control options used against, specific life stages of *Tuta absoluta* in Africa based on current bibliography ("x": associated with / used against; "-": not associated with / not used against).

Fortuitous natural enemies and IPM tools	Eggs	Larvae	Pupae	Adults
Fortuitous natural enemies				
Parasitoids	x	x	-	-
Predators	x	x	-	-
Natural enemy release				
Parasitoids	x	-	-	-
Predators	x	x	-	-
Pheromone-based tools	-	-	-	x
Prophylactic / cultural tools	-	-	x	x
Insecticide applications				
Biopesticides	-	x	x	-
Synthetic insecticides	-	x	-	-

potentially be used in a biological control approach (Table 1). In this framework, several new host-natural enemies associations have been discovered.

4.1 Northern Africa

A survey of native *Trichogramma* spp. (Hymenoptera: Trichogrammatidae), generalist egg parasitoids, in open-field tomato crops in oases of southwestern Tunisia recorded *Trichogramma bourarachae* Pintureau and Babault parasitizing *T. absoluta* eggs on tomatoes (Zouba et al. 2013b). In another study in Tunisian tomato-growing areas (Center, Centereast and Northeast), two indigenous larval ectoparasitoid species were found developing on *T. absoluta, Bracon* sp. (Hymenoptera: Braconidae) attacking mature larvae, and *Necremnus* sp. nr *artynes* (Hymenoptera: Eulophidae) attacking first, second and third instar larvae, the latter being the most abundant species (Abbes et al. 2014). No egg or pupal parasitoids were recorded in this study. In geothermal tomato greenhouses of southern Tunisia, both adult and nymphal stages of the indigenous predator *Nesidiocoris tenuis* (Reuter) (Hemiptera: Miridae) were found attacking eggs and larvae of *T. absoluta* (Ettaib et al. 2016). The study demonstrated that this predator (adult and nymphal stages) has a clear preference for *T. absoluta* eggs and that third instar nymphs prefer first and second instar larvae of *T. absoluta* over other leafminer's life stages.

Guenaoui et al. (2011a; 2011b) reported the following species of natural enemies developing or feeding on *T. absoluta* in tomato crops in northwestern Algeria: the eulophid parasitoids *Hemiptarsenus zilahisebessi* Erdos, *N. artynes*, which was the most abundant parasitoid species, *Neochrysocharis formosa* (Westwood), and *Stenomesius* sp., and the mirid predators *Macrolophus pygmaeus* (Rambur), *M. caliginosus* Wagner, *Dicyphus tamaninii* Wagner, and *N. tenuis*. Furthermore, a survey of natural enemies conducted in tomato greenhouses in the region of Mostaganem (northwestern Algeria) showed the presence of three mirid predators: *N. tenuis*, which was the most abundant species, *M. pygmaeus* and *Dicyphus errans* (Wolff), and the seven following parasitoid species: *N. artynes*, which was the most frequent and abundant species, *Hyposoter didymator* Thunberg (Hymenoptera: Ichneumonidae), *Neochrysocharis* sp., *Sympiesis* sp., *Diglyphus isaea* Walker (Hymenoptera: Eulophidae), *Bracon* sp., and *Trichogramma* sp. (Boualem et al. 2012). These authors indicated that the second instar larva was the most parasitized life stage, while the lowest parasitism rates were observed in fourth instar larvae.

Studies investigating *T. absoluta* natural enemies in Morocco are scarce. Three predators are frequently used for the biological control of *T. absoluta* in protected tomatoes in this country, i.e., the predatory mirids *N. tenuis* and *M. caliginosus* and the predatory mite *Amblyseius swirskii* Athias-Henriot (Mesostigmata: Phytoseiidae) (ONSSA 2010). However, only *N. tenuis* seems to be a common predator of *T. absoluta* (Elaini 2011, Ouardi et al. 2012).

In Egypt, the most complete study on parasitoids and predators has been that of Eman et al. (2016), who collected the larval parasitoid *Diglyphus* sp., two species of the larval-pupal parasitoid *Elasmus* spp. (Hymenoptera: Eulophidae) and the egg parasitoid *Telenomus* sp. (Hymenoptera: Platygastridae). They also abundantly found the predatory bug *N. tenuis* and provided data on its population dynamics and predatory efficiency. Other fortuitous natural enemies of *T. absoluta* found in Egypt include the parasitoids *Bracon nigricans* Szépligeti and *Trichogramma euproctidis* Girault (Zappalà et al. 2013, El-Arnaouty et al. 2014).

4.2 Eastern Africa

Several hymenopterous parasitoid species belonging to different families (Chalcididae, Bethylidae, Braconidae, Eulophidae) and the mirids *N. tenuis* (Reuter) and *M. pygmaeus* have been found attacking various developmental stages of *T. absoluta* in Kenya, although the parasitism level was low (Kinyanjuiet & Mohamed, S., unpublished data). The parasitoids *B. nigricans*, *B. hebetor*, *Dolichogenidea appellator* (Telenga) (Hymenoptera: Braconidae), *Ecdamua cadenat* (Risbec) (Hymenoptera: Torymidae), *Neochrysocharis formosa* (Westwood), and the predators *N. tenuis* and *Macrolophus* sp. were found associated with *T. absoluta* in Sudan (Mahmoud et al. 2013, Idriss et al. 2018). Moreover, Idriss et al. (2018) evaluated the performance of the two native braconid parasitoids, *B. nigricans* and *D. appellator*, against different immature stages of *T. absoluta* under laboratory conditions. Both parasitoids readily attacked the new host in the laboratory with parasitism levels up to 55% and by showing a differential preference for *T. absoluta* larval instars, i.e., early larval instars for *D. appellator* and later instars for *B. nigricans*. This can support the hypothesis that the *T. absoluta* biological control role of these two parasitoid species is synergistic in the field.

4.3 Western Africa

In Senegal, *N. tenuis* was detected feeding on *T. absoluta* for the first time in 2014 (Sylla et al. 2016). To date, it is the only effective predator detected in Western Africa. Field monitoring in Senegal indicated that 80% of *T. absoluta*-infested tomato fields in the 'Niayes' area also host *N. tenuis*. In Nigeria, the most abundant natural enemy observed in five sampled states was *N. tenuis*, followed by *D. errans* (Oke & Oladigbolu 2018a). A survey of *T. absoluta* natural enemies conducted in Nigeria in September 2015 allowed identifying larval braconid parasitoids of the genera *Apanteles* and *Bracon*, as well as egg parasitoids of the genus *Trichogramma* (Oke et al. 2016).

4.4 Southern and Central Africa

In 2017, surveys for *T. absoluta* natural enemies in heavily infested and abandoned tomato fields in South Africa (Limpopo and Gauteng provinces) recovered six species of indigenous parasitoids and a predatory bug (Nofemela R. unpublished results). No egg parasitoid was recorded in those surveys. Among the recovered natural enemies, the predator *Rhynocoris segmentarius* (Germar) (Hemiptera: Reduvidae) and the pupal parasitoid *Hockeria* sp. (Hymenoptera: Chalcididae) are being tested for their potential as biological control agents of *T. absoluta* in South Africa.

5 Current integrated management options

In Africa, *T. absoluta* is currently managed mainly by applying synthetic insecticides, but also implementing and integrating other approaches, such as prophylactic and cultural practices, use of pheromone-based trapping systems for early detection, monitoring and/or mass trapping, biological control using either generalist predatory bugs or with egg parasitoids, and application of microbial-based or plant extract-based insecticides (Table 1).

5.1 Prophylaxis and cultural practices

To prevent severe infestations by *T. absoluta*, it is always recommended to integrate prophylactic and cultural control measures in holistic and sustainable Integrated Pest Management (IPM) programs. In Senegal, farmers prefer to avoid growing tomato during late dry season, as it is the riskiest period for *T. absoluta* infestations. Field survey of the pest throughout the year showed a drastic decline of *T. absoluta* populations during the rainy season. This can be due to the decrease of resource availability, especially tomato crops that are less planted during the rainy season owing to susceptibility to foliar diseases. However, alternative hosts, such as eggplant and Ethiopian eggplant, can provide reservoirs for residual populations of the pest. Efforts should be focused on the management of such residual populations, e.g. by removing old eggplant plantations, to slow down the reconstitution of populations at the early dry season (Sylla et al. 2018).

The use of insect-proof screens has been shown to prevent and/or limit *T. absoluta* infestations on host plants in Tunisian (Cherif et al. 2013) and Moroccan tomato greenhouses (Ouardi et al. 2012) as long as nets are well maintained and windows screened. In Nigeria, however, Oke et al. (2016) observed that several commercial screen houses are built with large nets (1 × 4 mm) that allow *T. absoluta* entering into the crop. In Eastern Africa the use of insecticide-impregnated nets has been widely applied against mosquitoes and it was recently introduced to control crop pests, such as aphids (Martin et al. 2013). Although pyrethroid-treated nets have been proven to have sublethal effects on adults of *T. absouta* (Biondi et al. 2015), this tool has not been implemented in practice yet.

Usually, the use of resistant tomato cultivars in plant breeding programs could be a promising tool for controlling *T. absoluta*, as it was already proven in the tomato variety screening by Sohrabi et al. (2016). In this context, Cherif et al. (2013) suggested the use of tomato cultivars with lower suitability for oviposition by *T. absoluta* (eg.

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cv. Shams or cv. Chebli) as a promising prophylactic control tactic against *T. absoluta* in northeastern Tunisian tomato greenhouses. In Morocco, it has been suggested that the destruction of weeds (secondary hosts for *T. absoluta*), crop residues and infested plant material could help avoiding or reduce attacks of greenhouse and open-field tomato crops (Ouardi et al. 2012). Additionally, covering the soil with plastic screens that can help avoiding emergence of adults from buried pupae residing in the soil, and removing infested leaves and secondary shoots are considered as efficient cultural control practices against *T. absoluta* in Tunisia (Abbes et al. 2012).

5.2 Pheromone-based tools: early detection, monitoring and mass trapping

Traps baited with sex pheromone lures can be used for early detection of *T. absoluta* in newly invaded areas (Machekano et al. 2018). When the insect is established in a region, the same tool is then used for pest population monitoring purposes. This involves the follow-up of male flight activity during the growing season, which aims at deciding the most appropriate timing for applying either insecticide treatments or, alternatively, biorational control options (Caparros Megido et al. 2013).

In open-field tomato crops of northeastern Tunisia, *T. absoluta* males are monitored using at least two sex pheromone water traps (Pherodis®) per ha (Cherif & Grissa-Lebdi 2017). These authors indicated that insecticide sprays can be triggered based on pheromone monitoring data: when water trap catches reach a threshold of 50 males per trap per week, insecticides should be applied in tomatoes, as recommended by the Tunisian Ministry of Agriculture. Similarly, Ouardi et al. (2012) suggested, as a component of the national IPM action plan, the use of two pheromone-baited delta traps per ha for monitoring *T. absoluta* in Moroccan tomato crops. In Biskra region (northeastern Algeria), three pheromone delta traps per 400 m^2 tomato greenhouse (two at the entrances and one in the center) or two pheromone delta traps per 200 m^2 were used to detect the first adult male flights and to study population fluctuations (Allache et al. 2012, 2017). In Menoufia region (northern Egypt), three water traps baited with *T. absoluta* sex pheromone placed in a 2100 m^2 tomato field crop area were very useful to follow male flight activity from early April to early July (El-Aassar et al. 2015).

Mass trapping, using 32 traps per ha, was tested against *T. absoluta* in open-field industrial tomatoes in Central Tunisia. Results showed that the pheromone lure TUA-Optima® loaded with 0.8 mg of synthetic pheromone was more attractive to males of *T. absoluta* and should be used with high population levels compared to standard lures Pherodis® and TUA-500® with 0.5 mg of pheromone, which can be used in crops with lower *T. absoluta* population densities (Chermiti & Abbes 2012). According to Ouardi et al. (2012), in Morocco, it is recommended to use 20–25 pheromone traps per ha in tomato greenhouses and 40–50 pheromone traps per ha in open-field tomato crops. In open-field tomato crops of Giza governorate (northern Egypt), the mean percent fruit damage was significantly reduced after applying mass trapping of *T. absoluta* males using 8 pheromone-baited (0.5 mg) water traps per 4200 m^2 (Taha et al. 2013). Experimental water-light traps had a comparable efficacy in decreasing the pest damage compared to various combinations of synthetic insecticides used in Nigeria (Oke & Oladigbolu 2018b). However, in South Africa, two pheromone products and one in combination with cypermethrin are registered, but their implementation for mass trapping and/or action threshold is not yet achieved.

A possible alternative to mass trapping is the use of pheromone-based mating disruption technique (i.e. confusing males, disrupting mate location and avoiding/ reducing mating). This biorational, residue-free control approach showed great success against *T. absoluta* in tomato greenhouses in both Spain and Italy (Vacas et al. 2011, Cocco et al. 2013). Besides, the performance of attract(lure)-and-kill technique using the combination "synthetic sex pheromone + insecticide" could also be tested as a novel management tool against *T. absoluta* in African tomato-producing areas.

5.3 Releases of natural enemies

Three biological control approaches could potentially be used against *T. absoluta* in Africa (Van Driesche & Bellows 1996). Native natural enemies could be mass-produced for regular releases in field affected by the pest (augmentative biological control). The action of natural enemies present in the crops could be enhanced through the adaptation of specific cultural practices (conservation biological control); and exotic natural enemies from the pest native range could be introduced in Africa for permanent establishment (classical biological control).

Although these biological control options show a promising potential for the control of *T. absoluta* in Africa, so far only augmentative biological control is being applied, and exclusively in Northern Africa. The two categories of natural enemies that are being applied with some success are egg parasitoids and predatory bugs. The egg parasitoids *Trichogramma* spp. were shown to be promising biocontrol agents against *T. absoluta* in Tunisia. A release rate of 20 *T. cacoeciae* per plant was effective in reducing overall insect's life stage densities and infestation levels caused by this pest in protected and open-field tomato crops in the Cap-Bon region, the largest tomato-producing area in Tunisia (Cherif et al. 2018c). In protected tomato crops grown in southwestern Tunisia, a reduction of 87% and 78% in leaf damages was observed after releasing a total of 25.000 adults of either parasitoid *T. cacoeciae* or *T. bourarachae*, respectively (Zouba et al. 2013a). El-Arnaouty et al. (2014) tested the efficiency of three release rates (25, 50 and 75 parasitoids per m^2) of the indigenous *T. euproctidis* and *T. achaeae* against *T. absoluta* in northern Egyptian greenhouse tomato crops. They found that both *Trichogramma* species were significantly efficient, particularly at higher release rates, in reducing *T. absoluta* mines, and they suggested including the use of *T. euproctidis*, an autochtonous well-adapted species to local environment, in IPM and biocontrol programs of *T. absoluta* in Egypt.

In addition to egg parasitoids, predatory mirids were shown to be promising biocontrol agents against *T. absoluta* in Northern Africa. Ettaib et al. (2016) demonstrated that releases of *N. tenuis* in heated tomato greenhouses of southwestern Tunisia significantly decreased densities of *T. absoluta* eggs in tomatoes. In Moroccan greenhouses, it is recommended to perform one or two releases of *N. tenuis* at a rate of 1.5–2 individuals per m^2 (Ouardi et al. 2012). The use of *N. tenuis* as biocontrol candidate against *T. absoluta* is among the main components of IPM programs in greenhouses of the Souss region in southwestern Morocco (Elaini 2011). However, it should be taken into account that level of predator's efficacy may depend on tomato plant cultivar. Indeed, a recent study showed that predator (*Orius albidipennis* Reuter) efficacy in low dense trichome cultivars was significantly higher than that in high dense trichome cultivars (Salehi et al. 2016).

Interestingly, previous studies provided evidence that the combined use of biocontrol agents (i.e. parasitoids, predators and microbials) could enhance their action against *T. absoluta* in tomatoes. Indeed, Kortam et al. (2014) demonstrated that the combined use of the parasitoid *T. achaeae*, the predator *M. caliginosus* and the microbial pesticide *Bacillus thuringiensis* Berliner, at the rates of 25 adults per m^2, 0.25 adult per m^2, and 1g per liter, respectively, resulted in a significant reduction of *T. absoluta* mines in greenhouse tomato crops in northern Egypt. Similar studies conducted in northern Egyptian open-field crops showed that the combination "*B. thuringiensis* var. *kurstaki* + release of the parasitoid *T. evanescens* Westwood (70–75 adults/m^2) + pheromone mass trapping" significantly decreased densities of *T. absoluta* larvae and related damages in tomatoes (Khidr et al. 2013). Moreover, either combination "biweekly releases of *Trichogramma bactrae* Nagaraja + mass trapping" or "releases of *T. evanescens* + bioinsecticide treatment (Protecto and Spinosad bait)" significantly reduced infestation levels by *T. absoluta* in Egyptian open-field tomatoes (Goda et al. 2015, Rizk 2016).

In Western Africa, so far no *T. absoluta* natural enemies have been marketed, neither mass-reared, for biological control purposes. Nevertheless, some are marketed elsewhere in Africa, such as *N. tenuis* and *Trichogramma* spp. in Northern Africa. Some of the companies have distributors or subsidiaries in Sub-Saharan Africa (Kenya, Mozambique, South Africa, Zambia and Zimbabwe). Therefore, there is a strong potential for the development of *N. tenuis* and/or *Trichogramma* spp. release-based control methods in Western or Southern Africa in the future. Moreover, to the best of our knowledge no exotic natural enemies have been introduced in this area so far.

From a practical point of view, it would be appropriate to use a combination "parasitoids + predators" for strengthening the overall biocontrol action. A previous study in Europe demonstrated that *Trichogramma* parasitoids may not build up populations on the *T. absoluta* tomato system alone, but these parasitoids can be used in combination with the predator *M. pygmaeus* to enhance biological control of this pest in tomatoes (Chailleux et al. 2013). Nonetheless, the possible occurrence of intraguild predation should be taken into account before developing and applying any strategy based on the combined release of natural enemies.

Although several natural enemy species have been found forming new host prey-associations with *T. absoluta* in the new invaded range, including Africa, the search for co-evolved natural enemies of the pest in the native range should also be considered, as currently pursued for several invasive pest species worldwide (Daane et al. 2016, Hardwick et al. 2016, Konopka et al. 2017, Tena et al. 2017, Heimpel & Cock 2018). In this regard, ICIPE (Nairobi, Kenya) and the Federal Ministry for Economic Cooperation and Development (BMZ, Germany), led a *Tuta* IPM funded project, in partnership with the International Potato Center (CIP), (Lima, Peru). This project has the main aim to import into Kenya the *Microgastrine*, larval parasitoid, *Dolichogenidea gelechiidivoris* (Marsh) (= *Apanteles gelechiidivoris* Marsh, see Salas Gervassio et al. 2019) (Hymenoptera: Braconidae). The initial cohort of the colony of *D. gelichiidivoris*, which is currently maintained at Animal Rearing and Containment Unit (ARCU) of ICIPE, originated from a laboratory colony reared on *T. absoluta* at the CIP entomological laboratory in Lima. Laboratory *D. gelichiidivoris* host stage preference of this parasitoid showed that it prefers the early *T. absoluta* larval instar with an average parasitism rate of over 60% (Mohamed, S., unpublished data). Although field evaluations of this parasitoid are yet to be undertaken, the outstanding laboratory performance of this parasitoid indicates that *D. gelichiidivoris* is a promising classical biological control candidate against *T. absoluta*. Indeed, within its native range this parasitoid species has been recovered with high parasitism rates on *T. absoluta*. For example, in Colombia, *D. gelechiidivoris* is considered the most important biological control agent of *T. absoluta* with field parasitism rates reaching 76.6% (Valencia & Peñaloza 1990, Agudelo & Kaimowitz 1997, Vallejo 1999).

5.4 Insecticide applications and risk of resistance development

The application of insecticide treatments has been the most common control method adopted against *T. absoluta* in African tomato-producing areas. Insecticide formulations that have been used against *T. absoluta* can be based on (i) microbials (bacteria, fungi or virus) and microbial derivates, (ii) plant extracts (botanicals) or (iii) synthetic chemical active substances, alone or in combinations.

The microbial insecticides *B. thuringiensis* and spinosad exhibited satisfactory control of *T. absoluta* in tomato greenhouses of northeastern Tunisia (Grissa-Lebdi et al. 2011). In semi-natural conditions, *B. thuringiensis* var. *kurstaki* (250 g/hl) caused an average mortality between 72 and 80% on the three first instar larvae of *T. absoluta*, 7 days after treatment, while the new spinosyn, spinetoram (50 cc/hl), caused an average mortality of 85.6% on all *T. absoluta* instar larvae (Hafsi et al. 2012). More recently, Borgi et al. (2016) evaluated the insecticidal potential of a local (Tunisian) strain (P1) of the entomopathogenic fungus *Beauveria bassiana* Balsamo and a spontaneous mutant of this strain (P2) against *T. absoluta* larvae in laboratory conditions. They found that both strains were effective, but P2 showed stronger effect than P1, as it caused 100% of larval mortality within 5-day application. The development of insecticide based on this mutant (P2) should then be recommended as a new tool for the biocontrol of *T. absoluta* in Tunisia (Borgi et al. 2016). Several Tunisian and a Kenyan isolates of *Phthorimaea operculella* granulovirus (PhopGV) showed potential toxicity toward *T. absoluta* larvae in the laboratory, with estimated Lethal Concentration 50% (LC_{50}) ranging from 3.2×10^3 to 1.4×10^5 occlusion body/ml (Ben Tiba et al. 2018).

In Menoufia (northern Egypt) open-field tomato crops, the microbial-based insecticides *B. thuringiensis* (200 g/100 liter) and spinosad (75 ml/100 liter) were the most efficient in terms of control of *T. absoluta* larvae and reduction of related leaf and fruit damages, compared to the overall control effect of biopesticides based on the entomopathogenic fungi *B. bassiana* and *Metarhizium anisopliae* (Metsch.) (El-Aassar et al. 2015). As such it was proven that the combinations "*B. thuringiensis* var. *kurstaki* + Neem extract", "*B. thuringiensis* var. *kurstaki* + *Trichoderma harzianum* Rifai", or "*T. harzianum* + Neem extract" significantly reduced densities and damages of *T. absoluta* larvae in northern Egyptian open-field tomatoes (Khidr et al. 2013).

Extracts of plants grown in Africa may also exhibit insecticidal effects against *T. absoluta*. For example, the extracts of plants collected from the Souss valley in Morocco were tested for their potential in controlling *T. absoluta*. They included *Ricinus communis* L. (Euphorbiaceae), *Argania spinosa* L. (Sapotaceae), *Urtica dioica* L. (Urticaceae), *Thymus vulgaris* L. (Lamiaceae), *Ononis natrix* L. (Fabaceae), *Peganum harmala* L. (Nitrariaceae) and *Lawsonia inermis* L. (Lythraceae). The highest rates of mortality of *T. absoluta* larvae in laboratory conditions were produced by extract of *T. vulgaris* leaves (95% mortality) and the seeds of *R. communis* (58% mortality) (Ait Taadaouit et al. 2012, Nilahyane et al. 2012). Additionally, the essential oil of *Syzygium aromaticum* (L.) buds, a plant grown in Morocco, showed high insecticidal toxicity towards *T. absoluta* larvae in laboratory conditions, hence this plant extract could be incorporated in IPM programs against this pest in Morocco (Benchouikh et al. 2016).

Studies conducted in a Central-East Tunisian tomato greenhouse revealed that the insecticide indoxacarb (50 cc/hl) successfully controlled *T. absoluta* larvae (with more than 95% efficacy nine days after treatment), compared to either triflumuron (50 cc/hl) or diafenthiuron (125 cc/hl) (Braham & Hajji 2012). Besides, in north-eastern Tunisian tomato greenhouses, both chemical pesticides cyromazin (30 g/hl) and flubendiamid (30 g/hl) caused 96 and 77% *T. absoluta* larval mortality, respectively, three weeks after insecticide application, while the efficacy of azadirachtin did not exceed 40% (Cherif et al. 2018a). Among seventeen tested insecticides, the eight active substance formulations chlorantraniliprole, chlorfenapyr, indoxcarb, chlofenapyr mixed with indoxacarb, spinosad, spinosad mixed with abamectin, emamectin benzoate, and imidacloprid provided the most promising control results (> 90% average mortality) against *T. absoluta* larvae occurring in tomato open-field crops in Egypt (Moussa et al. 2013).

Chemical insecticides are mostly used to control *T. absoluta* in Sub-Saharan Africa. The Europe-Africa-Caribbean-Pacific Liaison Committee (COLEACP) initiated the evaluation of several insecticides (COLEACP, 2014, 2015). All countries have different pesticides registered for use against *T. absoluta* in tomatoes, however, in many cases products effective against this pest have yet to be registered. For instance, in 2016 the latest list of the Pesticide Sahelian Committee (CSP) authorized 11 synthetic insecticides in tomatoes: neonicotinoids (acetamiprid and imidacloprid), pyrethroids (lambda-cyhalothrin, cypermethrin and deltamethrin), organophosphates (profenofos, chlorpyrifos-ethyl, chlorpyrifos-methyl), a carbamate (methomyl), and two avermectins (abamectin and emamectin benzoate). Besides, three biopesticides are registered and available in Western Africa for the control of this pest; these are based on *B. thuringiensis*, neem extract and spinosad. A part from the microbial insecticide, most of these insecticides are mostly broad-spectrum for which the real *T. absoluta* control efficacy in Western Africa has not been described yet. Moreover, some of these insecticides have been banned in Europe for their adverse ecotoxicological effects (Ali et al. 2018), such as profenofos, which is one of the most used chemical active substances in tomatoes in Burkina Faso (Son et al. 2018).

In the Niayes area (northern coast of Senegal), the only method adopted by growers to control tomato insect pests, such as *T. absoluta*, is the application of synthetic (mostly broad-spectrum) insecticides including organophosphates, and to a lesser extent pyrethroids and avermectins. Nevertheless, results indicated that those insecticides were not effective in reducing pest's densities in tomatoes in this area (Diatte et al. 2018). The commercial insecticide on mixture of chlorantraniliprole and lambda-cyhalothrin was the first insecticide recommended and extensively used all over Nigeria for the control of *T. absoluta.* However, control failure was reported soon after. For example, Oke et al. (2017) reported that populations of *T. absoluta* from 7 major tomato-producing areas of Nigeria showed resistance to this agrochemical (resistance ratio ranging from 4.09 to 16.97 times), as well as to lambda-cyhalothrin (resistance ranging from 2.66 to 7.88 times) and to deltamethrin (resistance ranging from 2.23 to 6.24 times). Comparative open-field studies conducted in some Nigerian states (Kano, Kaduna, Katsina, Jigawa and Plateau) revealed that the combination of adult mass trapping, foliar sprays of *B. thuringiensis* and abamectin and applications of *M. anisopliae* to the soil was more efficient in controlling *T. absoluta* than several applications of phyretroids, chlorantraniliprole, flubendiamide and spirotetramat (Oke & Oladigbolu 2018c). Field surveys conducted in Kirinyaga County (Central Kenya) revealed that 94% of the farmers use synthetic insecticides as main control option for *T. absoluta*, with chlorantraniliprole (200 g/L) being the most applied active substance (Peris et al. 2018). In Central Ethiopian open-field conditions, applications of neem (*Azadirachta indica* (L.)) or *Allium sativum* L. botanical extracts, or the use of the entomopathogen fungus *B. bassiana* caused more than 70% of *T. absoluta* larval mortality, which significantly reduced leaf and fruit infestation (Shiberu & Getu 2018).

Although chemical broad-spectrum insecticide treatments have been commonly applied to cope with *T. absoluta* attacks in tomatoes worldwide (Desneux et al. 2011, Campos et al. 2017, Biondi et al. 2018), this control tactic usually proved to be neither effective nor sustainable, leading to dramatic increases in the number of necessary applications and pest control related costs (Potting et al. 2013) as well as to control failures. Since its arrival in Europe and Northern Africa, insecticide resistance in *T. absoluta* showed to be a major problem and a limiting factor in the development of control systems. Such situation is clearly the result of the selection pressure that this pest faced firstly in South America and subsequently in its areas of recent spread. Indeed, the early cases of resistance were reported from South America as a consequence of the intensive use, and overuse of organophosphate and pyrethroid insecticides (Salazar & Araya 1997, 2001, Siqueira et al. 2000, Lietti et al. 2005). Successively, low to moderate levels of indoxacarb resistance as well as high resistance to chitin synthesis inhibitors were detected (Silva et al. 2016). Later on, spinosad resistance reached high levels (Reyes et al. 2012, Campos et al. 2014) and more recently, resistance to diamides is spreading (Campos et al. 2015, Roditakis et al. 2018).

This scenario, where changes in the patterns of insecticide resistance followed the introduction of new chemistries to be used against *T. absoluta,* seems to be occurring in the newly invaded areas. In fact, at the time of its initial establishment in South European and North African countries, the control of *T. absoluta* was based mainly on broad-spectrum insecticides such as pyrethroids due to lack of specifically registered molecules. Thereafter, field collected populations in those regions showed high levels of resistance to pyrethroids and organophosphates (Haddi et al. 2012, 2017, Roditakis et al. 2013a) though these phenomena are more likely to be existent pre-invasion and introduced with the arrival of the first individuals in the area. Furthermore, recent reports of control failure to oxidiazines (Roditakis et al. 2013b), spinosyns and diamides (Roditakis et al. 2015, 2018) are clearly illustrating the high potential of this pest to develop resistance to multiple classes of insecticides.

In the Sub-Saharan countries, although only very few data on the cases of insecticide resistance are currently available, it is highly likely that the invasive nature and destructive potential of this pest, combined with the over-reliance on chemical control will lead to similar outcomes. In addition to resistance, other major pitfall linked to insecticide applications is that these chemical substances show detrimental side effects on native natural enemies, hampering their beneficial effects on pest populations and allowing the emergence of secondary pests (Arnò & Gabarra 2011, Biondi et al. 2012, 2013b, Wanumen et al. 2016, Cherif et al. 2018b, and see Desneux et al. 2007). Furthermore, insecticides can also exhibit adverse side effects on pollinators of tomato, including bumblebees and stingless bees (Mommaerts et al. 2006, Sarto et al. 2014, Ceuppens et al. 2015).

6 Research agenda for sustainable management

The invasive South American tomato pinworm is arguably the key, most devastating insect pest occurring in tomato-producing areas in Northern and Sub-Saharan Africa. In these geographical areas, *T. absoluta* has continued to spread rapidly since its first arrival in 2008, causing serious damages, substantial economic losses and, in certain circumstances, important food security issues. Although this alarming phytosanitary situation has incited researchers, growers and policy makers to deploy great efforts in an attempt to find the best approaches and tactics for suitably managing this major invasive pest, many crucial studies and actions are strongly warranted. For instance, the pest status in Western and Central African countries is still controversial and needs to be clarified as soon as possible. Moreover, the invasion history in this continent, as well as the population genetic structure behind this invasion is still unknown. Specific studies are thus needed in order to clarify these aspects. Untangling the genetic structure of the invading *T. absoluta* population(s) in Africa would also help understanding the propensity of this pest to develop insecticide resistance. This aspect is crucial because insecticide applications are still the most common approach adopted by growers to control *T. absoluta* in Africa. In South America and Europe, the extensive use of synthetic insecticides has led to the development of resistance to most insecticide classes and, in this regard, Africa is likely to face a similar outcome if nothing is done to reduce the overdependence on synthetic pesticides. This inevitably leads to higher crop protection costs and to side effects on non-target organisms, including farmers and consumers. For these reasons, the use of reduced-risk insecticide compounds, such as plant extracts or microbial-based selective insecticides (especially when locally available) and/or biorational alternatives are the most recommended approaches for achieving an effective control of *T. absoluta* in Africa and worldwide. Among the alternative control measures, the correct use of insect-proof nets (impregnated with insecticides or not), the use of pheromone-based tools (especially for mass trapping), the conservation and augmentation of indigenous biological control agents (especially generalist predators and egg parasitoids) should be integrated in *T. absoluta* IPM packages.

However, much more efforts are needed from researchers, policy makers, IPM practitioners, non-profit organizations and private companies to optimize the implementation of these tools. For instance, future actions should target: the development of standard protocols and the implementation of mass production of locally available biopesticides, based on plant extracts and/or microbials, and natural enemies (generalist predators and/or egg parasitoids); the identification of the optimal trap density for mass trapping; the potential identification of specific habitat management strategies (within farm and at the landscape level) in a conservation biological control approach aiming at increasing the natural presence of parasitoids and predators; further pre-release and post-release testing on the imported South American parasitoid, *D. gelechiidivoris*, and, in case of successful establishment in the new environment, satisfactory *T. absoluta* biological control, and least non-target effects, its intentional diffusion in other tomato-growing African areas should be promoted; the eventual identification of further species-specific and effective natural enemy species in the native range of *T. absoluta*, which could be considered for imports in Africa. Finally, the use of existing non-chemical control strategies needs to be promoted. The awareness of farmers and the governments should be significantly raised on the economic and environmental risks linked with the extensive use of pesticides and on the efficacy and sustainability of those alternative control tools. This would ultimately lead to economically profitable and sustainable control systems, thus increasing the quality of the life of small farmers and of their families, the local consumers as well as the quality of the tomatoes grown for extra-Africa exports.

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