

Current Strategies and Future Outlook for Managing the Neotropical Tomato Pest *Tuta absoluta* (Meyrick) in the Mediterranean Basin

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Abstract

The invasion of new regions by exotic pests has been more than ever a critical issue that warrants coordinated international actions to manage established populations and prevent further spreading. Invasive insects can undermine the ecological equilibrium of both natural and agricultural ecosystems. Moreover, increasing temperatures due to climatic change exacerbate this problem by allowing pests to further reach regions previously considered unsuitable. The tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera) is an exotic pest native to Peru that has spread beyond Neotropical America. In Europe, its occurrence was reported in Spain in 2006, and thereafter, it has spread throughout the Mediterranean Basin and further into Africa and part of Asia. While *T. absoluta* can cause losses to tomato production all over the globe, the differences in each invaded region (e.g., climate, vegetation) may affect its population dynamics and, consequently, management protocols. Therefore, the main intent of this forum paper is to explore how European growers and researchers are dealing with *T. absoluta* in the Mediterranean area. As for many other invasive pests, the best approach has been the adoption of integrated pest management (IPM). Specifically, the integration of biological control agents (e.g., mirid predators and egg parasitoids), microbial insecticides (i.e., *Bacillus thuringiensis*), selective chemical insecticides, and sex pheromone-based control has proven adequate, especially in tomato greenhouses. Nonetheless, some of the challenges ahead include the development of resistant tomato cultivars, the management of wild vegetation and companion plants to optimize the conservation of natural enemies and their effectiveness at the crop level, the management of insecticide resistance, and the improvement of sex pheromone-based tactics.

Introduction

Biological invasions have been associated with rapid global change and may contribute to biodiversity loss, disruption of ecosystem services, and degradation of natural and agricultural ecosystems (Pyšek & Richardson 2010, Paini *et al* 2016). Nonetheless, an invasive species faces a number of obstacles to becoming established in a new area. For example, it must

be able to reproduce, disperse, and successfully compete with resident biota (Van Kleunen *et al* 2010). Conversely, similarities in habitat and climate between the native and invaded regions are important determinants of invasion success. Lastly, cultural influence, regional history (di Castri 1989), and socioeconomic activities (e.g., trade and tourism) also concur to the final outcome of the invasion (Thuiller *et al* 2005). For example, Paini *et al* (2016) indicate that the level

of international trading and the size of a country's agricultural area are positively correlated with the rate of species invasions. On the other hand, introduced species have in general fewer natural enemies in respect to the native region (Torchin & Mitchell 2004), and recent cases of invasive pests indicate that local antagonists need time to adapt to the invader, which is often associated with consistent economic losses (Toepfer & Kuhlmann 2004, Francati *et al* 2015, Miller *et al* 2015, Dieckhoff *et al* 2017).

The South American tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is an invasive species that has received substantial attention, being considered one of the most devastating pests of tomato (*Solanum lycopersicum* L.) crops ever (Desneux *et al* 2010, 2011, Guedes & Picanço 2012). The pest is native to the highlands of Peru (Vargas 1970) but invaded other Latin American countries, such as Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Panama, Paraguay, Peru, Uruguay, and Venezuela, between 1960 and the 1980s (USDA-APHIS 2014). Despite being considered a tropical species and unlikely to invade temperate climate regions, *T. absoluta* has become a key pest of tomato crops in Europe (Desneux *et al* 2010, Campos *et al* 2017). *Tuta absoluta* was reported in eastern Spain in 2006, since then it has invaded other European countries and spread throughout the Mediterranean Basin (Desneux *et al* 2010). Central Chile is the most likely source of the *T. absoluta* populations that invaded Europe (Guillemaud *et al* 2015). Currently, this pest is also present in the Middle East, Africa, and parts of Asia (Biondi *et al* 2018, Shashank *et al* 2018), confirming its high capacity for spreading and adapting into new areas.

The larvae of *T. absoluta* feed on the tomato leaves, stems, and fruits; the injuries can result in production losses up to 80–100% (López 1991, Picanço *et al* 1998). The larval phase consists of four instars, and the mature larvae usually pupate in the soil. The adult moths generally remain hidden within the vegetation during the day, showing increased crepuscular flight activity and a preference for mating at the beginning of the photophase (Lee *et al* 2014). The life cycle from egg to adult takes 26–38 days in the field to complete, and overlapping generations are commonly observed (Guedes & Picanço 2012).

Despite investigations for setting up sustainable strategies of pest management, *T. absoluta* is still mainly controlled in South America by spraying insecticides that add to treatments needed to control the numerous tomato pests in this area (Siqueira *et al* 2000a, Guedes & Picanço 2012). Nevertheless, chemical control is often undermined by the insecticide resistance (Siqueira *et al* 2000b, Silva *et al* 2011) and by reduced contact of the toxic compounds sprayed on the vegetation with the larvae concealed within the mines digged into the leaves, stems, or fruits. Before its arrival in Europe, biological control of

T. absoluta using egg parasitoids (Hymenoptera: Trichogrammatidae) (Parra & Zucchi 2004, Medeiros *et al* 2006) and entomopathogens (i.e., *Bacillus thuringiensis*; Branco *et al* 2001) was already being investigated in South America (i.e., Brazil). However, the efficacy of these biological control agents in open fields remained questionable in many cases. More recently, Neotropical species of predatory pirate bugs (Heteroptera: Anthocoridae) and mirid predators (Heteroptera: Miridae) have also been considered as potential biocontrol agents of *T. absoluta* (Queiroz *et al* 2015, van Lenteren *et al* 2018b), but further studies are needed to assess their actual impact on *T. absoluta* in South American fields and greenhouses.

Although European researchers and growers can learn much from the South American experience on *T. absoluta*, many aspects remain to be investigated to set up protocols for the sustainable management of this pest. Additionally, various differences exist between South America and Europe, including climatic variables, production systems, and resident biota associated to tomato crops. In this context, collaborative and interdisciplinary efforts are required to exchange information and share results that indicate reliable strategies for managing *T. absoluta*. The main aim of this forum paper is to discuss how growers and researchers are tackling the management of the invasive species *T. absoluta* in the Mediterranean region.

Strategies Adopted to Manage *Tuta absoluta* in the Mediterranean Basin

The arrival of the pest: the initial reliance on chemical control and associated issues

Soon after its first appearance in Spain in 2006, and during its explosive spread throughout the Mediterranean Basin in only 3–4 years, chemical control of *T. absoluta* was the only approach used by tomato growers to maintain pest populations below the action threshold. Consolidated protocols of tomato integrated pest management (IPM) were revised to include up to 15 additional insecticide applications specifically targeting *T. absoluta* (Desneux *et al* 2011, Abbes *et al* 2012).

Chemical control of *T. absoluta* in the Mediterranean region was based, and still is, on the use of insecticides belonging to a few distinct chemical classes with different modes of action, namely diamides (chlorantraniliprole and, limited to some countries, cyantraniliprole), avermectins (abamectin and emamectin benzoate), spinosyns (spinosad), and oxadiazines (indoxacarb) (Roditakis *et al* 2018). Recently, semicarbazones (metaflumizone), with a mode of action similar to oxadiazines, have also been registered. Pyrethroids have

been generally excluded from *T. absoluta* IPM protocols due to the high levels of resistance associated with mutations of the *para*-type sodium channel gene that occur at a high frequency in its European populations (Haddi *et al* 2012, Roditakis *et al* 2013).

First failures in the chemical control of *T. absoluta* infesting greenhouse tomato began to be reported in 2012 in Sicily (Italy). In this region, the control strategy relied on repeated applications of chlorantraniliprole to which a high level of resistance was found among field populations (Roditakis *et al* 2015). Resistant populations to this insecticide were also found in the same period in Brazil (Silva *et al* 2016). During the last years, a trend toward an increasingly widespread resistance to chlorantraniliprole has been observed, with resistant populations recorded in Italy, Greece, and Israel (Roditakis *et al* 2018). These authors also reported the first indications of resistance to indoxacarb, spinosad, and emamectin benzoate in the Eurasian region. Conversely, it was evident that in some regions, regardless of the huge acreage covered by intensive tomato crops, no resistance to diamides was recorded. The reason has been found in the approach followed in these areas since the initial appearance of the pest. In Spain, for example, a major effort was made to adopt immediately an IPM strategy against *T. absoluta* outbreaks that did not exclusively rely on the use of insecticides but was based on a combination of pest monitoring for the correct timing of insecticide applications, biological control using the inoculative release of mirid predators in greenhouse crops, cultural control by deploying insect-proof nets on greenhouses, and the rotation of insecticides with different modes of action and reduced non-target effects (Perez-Hedo *et al* 2017, Roditakis *et al* 2018). This approach produced none or minimal selection pressure toward insecticide-resistant *T. absoluta* genotypes, with significant advantages for insecticide efficacy. The exclusive use of insecticides soon revealed ineffective and not viable in the long term because of several concomitant factors, including the endophytic and cryptic behavior of *T. absoluta* larvae; the high reproductive potential and capacity for explosive population outbreaks; the long period of fruit susceptibility; and the occurrence of resistant populations, particularly in the open field (Haddi *et al* 2012, Roditakis *et al* 2015) as already reported for South America (Siqueira *et al* 2000a, b, Lietti *et al* 2005, Guedes & Picanço 2012). The frequent harvest losses, despite insecticide applications, and the heavy environmental impact linked to the indiscriminate use of chemical insecticides prompted the adoption of alternative strategies, either substitutive or complementary to insecticides, to accomplish a successful control of *T. absoluta* (Desneux *et al* 2010). In this scenario, the 'Spanish' example has been a driving force toward the adoption of IPM approaches in all European Mediterranean countries.

Toward a biological control-based IPM strategy

Mirids as biocontrol agents: advantages and issues

The turning point in the control of *T. absoluta* in the Mediterranean region has been the consideration that mirid predators could be highly effective biocontrol agents of this pest. *Nesidiocoris tenuis* (Reuter), *Macrolophus pygmaeus* (Rambur), and some species of the genus *Dicyphus* (Hemiptera: Myridae) are generalist predators, endemic to the Mediterranean area, which are commonly associated with tomato crops from the spring to autumn seasons, when they feed on and contribute to the control of different pests (e.g., aphids, whiteflies). After the arrival of *T. absoluta*, mirid predators quickly adapted to prey upon the eggs and young larvae of this pest (Arnò *et al* 2010, Urbaneja *et al* 2012, Jaworski *et al* 2015). At that time, *N. tenuis* and *M. pygmaeus* were already being mass-reared and commercially available for growers, particularly for the control of whiteflies in tomato greenhouses, but the impact on the populations of *T. absoluta* was also immediately visible. To date, at least on greenhouse tomato, the damage of *T. absoluta* is generally lower in European districts where IPM programs based on the augmentation and conservation of mirid predators are being implemented (Zappalà *et al* 2013, Biondi *et al* 2018) in respect to those where these predators are not considered.

Nevertheless, mirid augmentation in tomato greenhouses poses some questions related to their zoophytophagous behavior which alternates insect prey and plant as a food source. Specifically, mirid nymphs and adults are able to feed on different plant parts (stem, sprouts, fruits, leaf, and flower peduncles), causing necrotic rings and consequent abortion of flowers and small fruits and reduced vegetative growth (Castañé *et al* 2011 and references therein). There is a heightened risk of crop damage associated with phloem feeding when mirid populations increase and insect prey availability is low; in these cases, insecticide sprayings are sometimes needed to avoid economic losses (Perez-Hedo & Urbaneja 2016). The impact of the phytophagous behavior of mirids on tomato is species-specific. For example, plant feeding and damage by *M. pygmaeus* and *Dicyphus* spp. are generally much lower than those caused by *N. tenuis*, and economic losses related to the former two species have been less frequently reported for commercial crops (Castañé *et al* 2011). However, regardless of the possibility of crop damage and the perception in some areas of *N. tenuis* as a potential pest, this predator is increasingly being released in tomato greenhouses in the Mediterranean region, particularly in southern Spain (Perez-Hedo *et al* 2017). Indeed, the potential risk of crop damage by *N. tenuis* is now considered to be largely counterbalanced by the beneficial effects of its introduction into IPM programs. For example, this species can persist on tomato crops even when the density of the target pest

T. absoluta is low, because it is able to feed on other insect pests, such as aphids, leaf miners (e.g., *Liriomyza* spp.), noctuid eggs and young larvae, herbivorous mites (e.g., *Tetranychus* spp.), and, although to a lesser extent, thrips, therefore substantially contributing to the control of these pests. In particular, mirids are highly effective in controlling key species of whiteflies, such as *Bemisia tabaci* (Gennadius) (an important vector of geminiviruses) and *Trialeurodes vaporariorum* (Westwood), which usually occur simultaneously with *T. absoluta* in tomato greenhouses (Arnò *et al* 2010, Bompard *et al* 2013). Moreover, the phytophagous behavior facilitates their persistence in the crop when the presence of prey is low. Finally, as the use of insecticides has been drastically reduced in regions where mirid predators are augmented, other natural enemies living in the surrounding landscape can spontaneously colonize crops in un-screened greenhouses, contributing to the sustainable control of tomato pests (Giorgini & Viggiani 2000, Gerling *et al* 2001, Nannini *et al* 2006). Among these natural enemies, there are also indigenous parasitoid species that adapted to *T. absoluta* (Ferracini *et al* 2012, Zappalà *et al* 2012, 2013, Biondi *et al* 2013a, Chailleux *et al* 2017).

Multitrophic interactions, driven by plant volatiles, are also influenced by the phytophagous behavior of mirid predators. In response to mirid feeding activity, tomato plants release a blend of volatile compounds that modulates the behavior of insect pests and natural enemies. Mirid-induced defensive response is species-specific, with *N. tenuis* and *M. pygmaeus*-induced volatiles able to attract or repel pests and/or natural enemies in different ways. For example, both predator species induce tomato plants to produce volatiles that are repellant to *B. tabaci* and attractive to whitefly parasitoids. However, while the *N. tenuis*-induced response has no effect on *T. absoluta*, this latter is attracted by tomato plants infested with *M. pygmaeus* (Perez-Hedo *et al* 2015, Naselli *et al* 2016, Perez-Hedo *et al* 2018).

Mirid augmentation

The most common strategy followed for *N. tenuis* and *M. pygmaeus* consists into inoculative releases, usually starting a few weeks after seedling transplanting. This timing allows to build up a consistent population of the predator before the outbreak of *T. absoluta* (Urbaneja *et al* 2012, Perez-Hedo *et al* 2017). There are advantages and disadvantages associated to the augmentation of either *N. tenuis* or *M. pygmaeus* in tomato greenhouses. *Nesidiocoris tenuis* establishes in an easier way in respect to *M. pygmaeus* as populations can increase even when *T. absoluta* is the only available prey (Mollà *et al* 2014). Conversely, the population growth of *M. pygmaeus* relies on the co-occurrence of alternative prey species in the crop, such as whitefly (Alomar *et al* 2006, Jaworski *et al* 2015, Sylla *et al* 2016). However,

M. pygmaeus is sometimes preferred to *N. tenuis* where the paucity of prey following the introduction of mirids may stimulate an excessive phytophagous behavior, possibly leading to crop damage.

A different inoculative strategy, referred to as “predator-in-first” has been established for *N. tenuis*, which consists in the release of predators within seedling nurseries, so that when tomato plants are transplanted in the field they already carry the eggs of the predators (Calvo *et al* 2012a, b). This method makes it possible to shorten the period required for the biocontrol agent to establish, and improves its distribution within the crop area, especially when weather conditions are not favorable. However, as mentioned before, this strategy requires a constant monitoring and management of the mirid population to avoid crop damage linked to high population densities (Perez-Hedo *et al* 2017). At low density of the target pest, a fast establishment of mirid predators with low risk of crop damage can be obtained by providing supplementary food (i.e., *Ephestia kueniella* Zeller eggs, alone or mixed with *Artemia franciscana* cysts) in the crops (Urbaneja-Bernat *et al* 2015, Brenard *et al* 2018).

Economic considerations on mirid augmentation and the use of conservation biological control

It is important to stress that the high effectiveness of mirid predator augmentation in Spain was also possible for the huge investments finalized to improve greenhouse structures toward types (i.e., modern Parral and multitunnel greenhouses) that can be screened on the sides with insect-proof nets while ensuring optimal ventilation and climatic regulation (van der Velden *et al* 2012). These greenhouses limit the entrance of *T. absoluta* and other pests, without causing excessive heat and/or humidity that could have negative effects on plant growth, health status, and production. However, if the mirid population density increases and insect prey is scarce, the presence of insect-proof nets can increase the risk of crop damage, as the mirids are unable to leave the greenhouse to search for other alternative prey (Castañé *et al* 2011). In such cases, it may be necessary to manage mirid populations with specific insecticides or supplementary food (see above).

With respect to the economic aspects of IPM, there are indications from Spain that biological control based on mirid augmentation in greenhouses with insect-proof nets is cheaper than chemical control, particularly when applied to long-cycle tomato cultivars (van der Velden *et al* 2012). In fact, in other Mediterranean regions, such as in Italy, mirid augmentation could be less convenient from an economic perspective, because of the shorter growing cycles of tomato crops. Predators need to be released at the beginning of the crop cycle, and the associated initial costs need to be compared against a shorter growing period and a lower yield (van

der Velden *et al* 2012). Moreover, tomato greenhouses in Italy often consist of low-tech structures on which insect-proof nets negatively alter the internal climate. On the other hand, these unscreened greenhouses allow wild natural enemies to colonize the protected tomato crops from the outside surroundings. In such context, conservation biological control is increasingly considered as a complementary or even alternative strategy to commercial augmentative methods (Messelink *et al* 2014), because wild natural enemies can enhance the effectiveness and economic viability of augmentative releases (Gerling *et al* 2001).

The establishment of generalist predators is favored by the high diversity of prey generally occurring in unscreened greenhouse or open field tomato crops (Symondson *et al* 2002, Messelink *et al* 2014). If these natural enemies from outside arrive earlier than *T. absoluta* on the crop, they contribute greatly to its control. Complex landscapes, characterized by wild herbaceous and shrub vegetation surrounding the tomato fields, highly contribute to the conservation of predators (Gabarra *et al* 2004, Lambion 2011, Ingegno *et al* 2013, Aviron *et al* 2016) and parasitoids (Gerling *et al* 2001, Nannini *et al* 2006). Many wild plant species, that are common in southern Europe, are hosts of mirid predators and support the migration of natural enemies to and from the crop, providing refuge, food, and alternative prey throughout the year during and at the end of crop cycles (Cano *et al* 2009, Ingegno *et al* 2009, Perdakis *et al* 2011). Natural mirid populations can be effective in controlling *T. absoluta* (Arnó *et al* 2009), not only in greenhouse but also in open field tomato cultivations. For example, in Israel, despite the high abundance of *T. absoluta* throughout the year, damage to processing tomato fruit can be very low if the activity of *N. tenuis* and other natural enemies is conserved by reducing the use of broad spectrum insecticides (Harpaz *et al* 2011).

In addition to the exploitation of natural plant biodiversity, the management of the agroecosystem with companion plants, grown on the field edge or intercropped with the tomato, can be exploited as well (Perdakis *et al* 2011, Messelink *et al* 2014, Ingegno *et al* 2017). For example, in the Mediterranean area, the cultivation of flowering strips of *Calendula officinalis* L. along the field edge favors the activity of mirid predators (and pollinators) on tomato crops and has been suggested as a strategy to increase the control of several pests, including *T. absoluta* (Lambion 2014, Balzan 2017). Similarly, sesame (*Sesamun indicum* L.) plants are very attractive for *N. tenuis* for feeding and oviposition, even in the absence of prey, and are potentially suitable for maintaining predator populations nearby tomato crops; further, using sesame plants in combination with augmentative release of *N. tenuis* may help to reduce predator dispersal toward non-crop habitats, or when predator populations become excessively large, to reduce the risk of crop damage (Biondi *et al* 2016, Naselli *et al* 2017).

The rational use of insecticides and the choice of selective compounds is pivotal in the effective conservation of mirids (and other natural enemies) in tomato fields. *Tuta absoluta* management often relies on the integration of mirid augmentation and/or conservation coupled with the use of selective *Bacillus thuringiensis* treatments, which do not interfere with predator and parasitoid establishment, and ultimately complement mirid activity during fruit harvesting (González-Cabrera *et al* 2011, Mollà *et al* 2011). Moreover, lethal and sublethal effects of synthetic insecticides on mirid predators differ among compounds (Arnó & Gabarra 2011, Passos *et al* 2017, Ziaei Madbouni *et al* 2017, Pérez-Aguilar *et al* 2018) with some of them resulting to be slightly or moderately toxic regardless of their efficacy in controlling the pest (e.g., spinosad, chlorantraniliprole) (Arnó & Gabarra 2011, Passos *et al* 2017). These compounds are thus sometimes used to integrate the activity of mirids and *B. thuringiensis* in IPM programs. Further, no effective bio-control agents exist for some pests that occur in Mediterranean tomato crops, such as the russet mite *Aculops lycopersici* (Massee) and the thrips *Frankliniella occidentalis* (Pergande), prompting the application of specific chemical treatments. In these cases, the use of acaricides or insecticides selective to mirid predators is of great importance to avoid the disruption of *T. absoluta* biological control (Arnó & Gabarra 2011, Mollà *et al* 2011, Ziaei Madbouni *et al* 2017).

Potential and challenges for egg parasitoid augmentation

Apart from mirid predators, egg parasitoids of the genus *Trichogramma* have received substantial attention in South America as potential biological control agents of *T. absoluta* (Parra & Zucchi 2004, Pratisoli *et al* 2005, Cagnotti *et al* 2016). In Mediterranean countries, *Trichogramma achaeae* Nagaraja & Nagarkatti and, limited to Egypt, *Trichogramma euproctidis* Girault have been considered as candidates to support *T. absoluta* management through inundative releases into tomato greenhouses (Urbaneja *et al* 2012, El-Arnaouty *et al* 2014, Kortam *et al* 2017). *Trichogramma achaeae* is mass-reared and commercially available, but there are factors limiting the success of its inundative use including the low fitness of parasitoids emerging from *T. absoluta* eggs, the low suitability of the tomato-*T. absoluta* system for supporting *Trichogramma* parasitoids, and the necessity of multiple releases resulting in high costs (Cabello *et al* 2009, Chailleux *et al* 2012, 2013). Moreover, the climatic conditions in the Mediterranean area and the low-tech greenhouses covered with plastic result in extreme fluctuations in daily temperature and relative humidity during the crop cycle, often being unsuitable for the parasitic activity of *T. achaeae* (Urbaneja *et al* 2012, de Oliveira *et al* 2017). Further, considering the extreme susceptibility of *T. achaeae*

and in general *Trichogramma* spp. to many pesticides (Fontes et al 2018), it is difficult to integrate egg parasitoid augmentation in IPM programs that relies on some insecticide application. In any case, the inundative release of *T. achaeae* in Mediterranean tomato greenhouses is considered a component of IPM to complement the activity of mirid predators (e.g., *M. pygmaeus* in France) especially in situations where predators alone do not guarantee an efficient control of *T. absoluta* (Chailleux et al 2013, Giraud 2015).

Tuta absoluta sex pheromone in tomato IPM

The sex pheromone of *T. absoluta* has been used in different applications within IPM programs, ranging from monitoring to pest control (Caparros Megido et al 2013), but its use is still limited in the Mediterranean region. Sex pheromone monitoring traps are used to assess the beginning of colonization and the population dynamics, which is fundamental information for the correct timing of control interventions. However, the number of male captures is not necessarily indicative of crop damage and cannot be associated to an economic threshold (Caparros Megido et al 2013). By contrast, Benvenga et al (2007) has proposed in Brazil an action threshold of 45 adults collected daily per pheromone trap in tomato fields. Nonetheless, alternative, easy-to-apply sampling methods for reliably estimating *T. absoluta* population densities are required to support the development of decision-making protocols (Biondi et al 2018 and references therein).

Mass trapping, most frequently applied by water traps lured with a sex pheromone dispenser, either associated or not with insect-proof nets in greenhouse, has been also considered as an important IPM component (Chermiti & Abbes 2012, Harbi et al 2012), although the results are highly variable in terms of effectiveness (Cocco et al 2012). These “uncertain” results often arise from the reproductive biology of the pest. For example, *T. absoluta* males are able to mate several times during their adult life cycle, and a very high number of captures is needed to achieve a consistent reduction in the oviposition rate. In addition, female polyandry and crop colonization by mated females can further reduce the effectiveness of mass trapping (Lee et al 2014), as it does the parthenogenetic reproduction that may occasionally occur in natural populations of the pest (Caparros Megido et al 2012, Abbes & Chermiti 2014). These considerations also apply to mating disruption, which has proved ineffective in preventing economic losses when applied in the open field or unscreened greenhouses (Vacas et al 2011). Conversely, in greenhouses with facades closed by insect-proof nets, mating disruption is fairly effective in managing *T. absoluta*, in combination with a reduced number of insecticide treatments (Cocco et al 2013, Sannino et al 2014). In some Mediterranean districts, where concomitant infestations of

thrips and *T. absoluta* are common in greenhouses not equipped with insect-proof nets, the combined use of mating disruption, introduction of *N. tenuis*, and treatment with *B. thuringiensis* prevent the negative consequences linked with chemical control of thrips. Indeed, reduced insecticide applications can be successful in thrips management while having a low impact on *N. tenuis*, whose temporary population reduction was compensated by mating disruption and *B. thuringiensis* treatments (Manco et al 2015). In the last 2 years, mating disruption (Isonet® T) has been increasingly applied in southern Italy, with over 1000 ha currently invested (Benuzzi M, CBC Europe, personal communication). This strategy, even in unscreened greenhouses, allows a consistent reduction in the number of insecticide applications, and is suggested in IPM guides issued by Italian plant protection extension services.

Future Outlook and Final Remarks

Despite the progress made in sustainable management of *T. absoluta* in southern Europe, there are control strategies still to be fully explored and potentially applicable (e.g., resistant tomato cultivars, entomopathogens, botanical insecticides) and others that should be better investigated to be implemented in the IPM of tomato crops (e.g., integration of selective pesticides with biological control agents; exploitation of companion plants to improve the conservation and the effectiveness of predators and parasitoids; augmentation of parasitoids; mating disruption). Long-lasting and effective management of *T. absoluta* in the Mediterranean area also depends on the strategy applied to control other tomato's pests. For instance, complications may arise when growers have to manage outbreaks of the thrips *F. occidentalis* and of the tomato russet mite *A. lycopersici*. These pests both lack effective natural enemies, and growers cannot avoid the use of synthetic insecticides (sometimes with a broad spectrum) to protect crops. This situation is further complicated by the detrimental impact of insect-borne viruses such as TYLCV and TSWV, which are transmitted by *B. tabaci* and *F. occidentalis*, respectively (Riley & Pappu 2004, Czosnek 2007). The occurrence of these viruses forces Mediterranean growers to adopt intensive insecticide application regimes to control vectors characterized by repeated sprays at close intervals, even if pests occur at low densities. In these cases, the activity of natural enemies can be disrupted, making the biological control of *T. absoluta* virtually impossible. The adoption of a global IPM strategy for all tomato pests is therefore fundamental to perpetuating natural enemy conservation and augmentation-based management of *T. absoluta*.

Plant breeding programs and identification of resistance traits

Within a successful IPM strategy against *T. absoluta*, plant breeding could have a dominant role in reducing insecticide inputs in the tomato systems. In this context, resistance traits to *T. absoluta* from accessions of tomato wild relative species are currently being exploited. The most promising ones rely on leaf metabolites (e.g., 2-tridecanone, zingiberene, and acylsugars) that have negative effects on both egg oviposition (antixenosis) and larval development (antibiosis) (Rakha *et al* 2017, Silva Ataide *et al* 2017, Biondi *et al* 2018 and references therein). The wild relative most used to develop resistant tomato cultivars are *Solanum pennellii* Correll and *Solanum habrochaites* Knapp & Spooner (de Azevedo *et al* 2003, Bleeker *et al* 2012, Dias *et al* 2013, Leckie *et al* 2014, Lima *et al* 2015). Moreover, screening for different commercial cultivars has raised the possibility that “partial resistance” to *T. absoluta* can be pursued in breeding programs and exploited within IPM strategies (Ghaderi *et al* 2017, Krechmer & Foerster 2017, Sohrabi *et al* 2017). Enhancement of tomato resistance to *T. absoluta* can be also obtained by the expression of insecticidal transgenes in tomato plants. The expression of *B. thuringiensis* protoxins Cry1Ab and Cry2Ab in tomato plants has been exploited against other lepidopteran pests (Saker *et al* 2011, Koul *et al* 2014) and could also be explored for managing *T. absoluta*. Recently, a modified *B. thuringiensis cry1Ac* gene has been introduced into tomato plants, which caused a high mortality of *T. absoluta* larvae and a reduced formation of leaf mines (Selale *et al* 2017). Additionally, knowledge gained from related species (i.e., potato) could be exploited to produce transgenic tomato plants. For example, the expression of the hybrid SN19 gene, which combines Cry1Ia and Cry1Ba proteins in potato, leads to enhanced resistance against *T. absoluta* (Ahmed *et al* 2017). Lastly, RNA interference also emerged as an alternative strategy to control *T. absoluta*, with transgenic tomato plants, expressing dsRNA molecules that target (silence) essential insect genes, resulting in a reduction of leaf damage (Camargo *et al* 2016). Recently, the expression in tomato plants of insecticidal transgenes of botanical origin (i.e., proteinase inhibitors from barley) has been shown to increase the resistance of tomato plants to *T. absoluta* without detrimental impact on the predator *N. tenuis* which resulted being attracted by the transformed plants (Hamza *et al* 2018). However, tomato genotypes that express direct defenses against *T. absoluta* may also have a negative impact on natural enemies (Bottega *et al* 2017), and thus, the feasibility of integrating host plant resistance with biological control in IPM programs should be carefully evaluated (Peterson *et al* 2016).

Although the use of resistant tomato varieties is desirable, to our knowledge, there are no varieties specifically

commercialized for their resistance to *T. absoluta*, at least in southern Europe. It should be considered, however, that to develop a sustainable control strategy for *T. absoluta* in the Mediterranean region, cultivation of tomato varieties with traits of TYLCV and TSWV resistance, now widely available for the growers, is far from being of secondary importance in reducing the economic and environmental impact of insecticide applications targeting the vector insects and in favoring the IPM of *T. absoluta*. All antagonists (released and wild populations) will benefit from the reduced use of insecticides, and thus, the possibility of combining the resistance to both *T. absoluta* and insect-borne viruses in breeding programs should be considered.

While resistance traits that directly affect pest fitness have been largely exploited in breeding programs, there has been a lack of awareness of the importance of indirect defenses, which have therefore been ignored. These include the characterization of herbivore-induced plant volatiles (HIPVs), which attract natural enemies to infested plants (Stenberg 2017). Recent studies have shown that the attraction of *N. tenuis* and *M. pygmaeus* to *T. absoluta*-infested tomato plants differs by predatory species, with the latter being more reliant on HIPVs to locate prey-infested plants (De Backer *et al* 2017, Naselli *et al* 2017). Unraveling the chemical cues involved in the interaction between infested plants and natural enemies opens up new opportunities in IPM to increase the activity of natural enemies in cultivated fields, by both direct use of HIPVs and enabling crop breeders to design cultivars suitable for specific biological control agents (De Backer *et al* 2017, Stenberg 2017). Similarly, the characterization of plant compounds involved in regulating oviposition behavior could be exploited in developing new IPM strategies (Khan *et al* 2008). For example, a recent investigation of the role of *T. absoluta* larvae-induced plant volatiles in the oviposition choice of conspecific females on tomato plants showed that female moths preferred to oviposit on intact rather than previously damaged plants (Anastasaki *et al* 2018).

The identification of potential compounds, such as HIPVs differentially expressed by tomato cultivars or constitutively produced by wild tomato plants, that act in deterring *T. absoluta* females (Proffit *et al* 2011, Anastasaki *et al* 2018) while attracting its antagonists should be considered in breeding programs for developing novel IPM strategies, such as the “push and pull” method (Khan *et al* 2008).

Contribution of parasitoid species to biological control

Different parasitoid species have been found to contribute to the biological control of *T. absoluta* in Europe as well as in invaded areas of South America. To date, no parasitoid species specialist on *T. absoluta* has been recorded in South America, hampering any attempt of classical biological

control program in invaded regions (Desneux *et al* 2010). Surveys for potential classical biocontrol agents in the native area of *T. absoluta* may therefore be valuable. However, many larval parasitoid species have been found to adapt to *T. absoluta* in the Mediterranean region (Zappalà *et al* 2012, 2013, Gabarra *et al* 2014). Consequently, implementation of conservation measures aimed at protecting and increasing the activity of these parasitoids needs to be considered. Some larval ectoparasitoids, namely *Necremnus tutae* (Ribes & Bernardo) and *Stenomesus japonicus* (Ashmead), have also been studied as potential biocontrol agents, as they are able to reproduce on and kill *T. absoluta* larvae efficiently (Ferracini *et al* 2012, Chailleux *et al* 2014), even when experiencing host competition with the mirid predators (Chailleux *et al* 2017). *Necremnus tutae* was initially mass-reared by some European companies and proposed as a biocontrol agent for inoculative release in tomato greenhouses. However, the high release rates required and the insufficient protection of fruits from larval boring made the use of *N. tutae* not sustainable (Calvo *et al* 2016). Moreover, mass production of this parasitoid proved very expensive because of the lack of suitable alternative hosts, and thus, it has been rapidly abandoned. Nonetheless, larval parasitoids could profitably complement the activity of natural mirid populations, pending the development of appropriate augmentation techniques and low-cost and productive mass-rearing technology.

Conversely, egg parasitoids of the genus *Trichogramma* (mainly *T. achaeae*) are easily mass-reared on alternative hosts (e.g., *E. kuehniella*) and represent suitable candidates to be implemented in IPM of *T. absoluta*. However, their low fitness in greenhouse crops requires multiple releases and a consequent possible lack of economic sustainability (Cabello *et al* 2009, Chailleux *et al* 2012, 2013). The efficiency of *T. achaeae* could be enhanced either by using specific host species for mass-rearing and temperature acclimation during parasitoid development (Cascone *et al* 2015) and also by choosing companion plants suitable for adult wasp feeding and recovery during the hottest hours of the day. A recent finding that *T. achaeae* females are attracted to a synthetic blend of *T. absoluta* sex pheromones (Gontijo *et al*, unpublished) suggests a possible use of *T. achaeae* inundative release in combination with mating disruption, targeting early infestation of *T. absoluta* and complementing the activity of feral or released mirid predators (Chailleux *et al* 2013, Giraud 2015). Lastly, further research on the biology, behavior, and chemical ecology of *T. achaeae* may help to increase its efficiency as a biocontrol agent.

Conservation of Tuta absoluta natural enemies

Natural enemies are an important factor of mortality regulating the populations of *T. absoluta* in invaded areas,

especially when their action is protected from pesticides side effects (Bacci *et al* 2018). In the Mediterranean region, generalist mirid predators represent the main biological control agents of *T. absoluta*, and the occurrence of wild vegetation surrounding tomato fields is fundamental for their conservation in the agroecosystem (see above). However, parasitoids too can be of some importance to control pest population in the crops, particularly larval ones (Zappalà *et al* 2013, Gabarra *et al* 2014). *Necremnus tutae* Ribes & Bernardo is frequently the most active parasitoid species (Zappalà *et al* 2012, Abbes *et al* 2014, Cocco *et al* 2015, Gebiola *et al* 2015) reaching parasitization rates as high as 75–80% in some contexts (Rizzo *et al* 2011, van der Blom *et al* 2016). Consequently, conservation of natural population of larval parasitoids appears of great interest to complement the activity of mirid predators. Flowering plants may be exploited by adult parasitoids as a source of nutrients (Balzan & Wäckers 2013), and it has been shown that some plant species benefit longevity and fecundity of larval parasitoids (e.g., *N. tutae*), without unwanted effects on the pest (Arnò *et al* 2018). Growing selected companion flowering plants may potentially favor the colonization of the crop by parasitoids and may be exploited to improve the biological control of *T. absoluta*. Recently, different flowering plants are being suggested as a component of the IPM of *T. absoluta* in Spain to increase the activity of *N. tutae* in greenhouse tomato (Crisol Martínez & van der Bloom 2018). It must be emphasized, however, that the knowledge on the ecology of larval parasitoids is still scarce including the role of their alternative hosts and their host plants. For example, *N. tutae*, which is considered the most frequent and active parasitoid in tomato crops, has been recorded so far only from *T. absoluta* (Gebiola *et al* 2015). A better knowledge of the trophic interactions among parasitoids, *T. absoluta*, and alternative insect hosts may greatly benefit the exploitation of the conservation strategy. Preservation of wild vegetation and introduction of companion plants bearing non-pest hosts, in combination with food-source flowering plants, might increase crop colonization by parasitoids (i.e., *N. tutae*) and the control rate of *T. absoluta*. Ideally, conservation of host plants of both parasitoids and mirid predators should ameliorate the control of *T. absoluta* with positive effects on biodiversity increase and agroecosystem resiliency to *T. absoluta* and other pests (Perez-Hedo *et al* 2017). In this view, to achieve a consistent reduction of fruit damage and yield losses, different factors must be considered in the management of the natural flora occurring in tomato agroecosystem and in the introduction of companion plants. In particular, it must be taken into account that some traits of the biology of mirid predators (oviposition in plant tissues, phytophagous behavior, inability to complete the development on some plant species in the absence of prey) require the occurrence of host plants suitable to sustain their

reproduction, nutrition (i.e., by sap and pollen), and overwintering. With these conditions, predators can persist in the agroecosystem and be able to colonize the crops earlier, and the risk of crop damage associated to plant feeding in the absence of pests is mitigated by the presence of alternative food (non-pest prey and plants with a high nutritional value) (Perdikis *et al* 2011, Biondi *et al* 2016). A complex of plant species is then required for effective conservation biological control of *T. absoluta*.

The choice of companion plants must also consider the possible fitness benefits for *T. absoluta* adults due to the nutritional resources provided by flowering plants. Further, some plant species (i.e., *Solanum nigrum*), that are natural hosts of mirid predators, are also able to support the complete development of *T. absoluta* (Perdikis *et al* 2011, Balzan & Wäckers 2013, Ingegno *et al* 2017). These unwanted side effects of increased plant biodiversity can be mitigated by choosing companion plants that are not attractive to *T. absoluta* (Arnò *et al* 2018). In the Mediterranean region, field margins characterized by complex assemblages of wild plants and occurrence of floral resources resulted in more complex communities of natural enemies, enhanced natural control of *T. absoluta*, and increased yields in tomato crops (Balzan & Moonen 2014, Balzan *et al* 2016a, b). Further, the exploitation of natural vegetation and companion plants should be carefully evaluated within the IPM of all tomato pests. Some plant species could promote population increases of other insect pests (Parolin *et al* 2013) or may act as reservoirs of plant pathogens (e.g., the viruses TYLCV transmitted by *B. tabaci* and TSWV transmitted by *F. occidentalis*). Research aimed at selecting plants that favor the persistence of predatory mirids and reduce the impact of mirids feeding on tomato plants should always consider the potential side effects of this conservation tactic, and alternative host plants for natural enemies should be selected according to their susceptibility and attractiveness to tomato diseases and pests (Cano *et al* 2009). For example, the use of *C. officinalis* as a companion plant of tomato (Lambion 2014, Balzan 2017) must be carefully evaluated in areas subjected to TSWV epidemics because this plant hosts both the vector *F. occidentalis* (Rahman *et al* 2010) and the transmitted virus TSWV (Parrella *et al* 2003). In regions where the harmfulness of key tomato pests is mainly associated with their ability to transmit viruses, control measures for tomato protection rely frequently on insecticide treatments and, for greenhouse crops, insect-proof nets. As these measures reduce arthropod biodiversity, conservation of natural enemies is difficult to implement inside crops if selective pesticides and tomato varieties resistant to viral diseases cannot be implemented. However, natural enemy conservation on wild vegetation may contribute to a reduction in pest populations in the environment surrounding the greenhouses. Landscape ecology associated to the study of the foraging behavior of pests

and antagonists is a field still in its infancy that could provide sustainable solutions for tomato management.

Use of insecticides based on selectivity

As the use of pesticides is frequently necessary in tomato IPM, the associated risks to natural enemies should be considered in setting up control strategies. In particular, selective insecticides should be preferred to protect mirid predator activity that is essential for *T. absoluta* control and to preserve the diversity of natural enemies of crop pests. Mirid predators can suffer lethal and sublethal effects by pesticides commonly applied to tomato crops (Martinou *et al* 2014). However, selectivity has been observed in some chemicals that are usually recommended against sucking insects (e.g., spirotetramat and pyriproxyphen) and mite pests (e.g., spiromesifen used against the russet mite). Further, some active ingredients recommended for IPM of *T. absoluta* in the Mediterranean region (e.g., azadirachtin, chlorantraniliprole, indoxacarb, spinosad) showed slightly or moderately harmful effects against mirid predators (Arnò & Gabarra 2011, Mollà *et al* 2011, Martinou *et al* 2014) and are frequently incorporated in IPM programs that rely on conservation and/or augmentation of mirid predators. Among these insecticides, chlorantraniliprole was also recommended for IPM of *T. absoluta* in South America because of the low toxicity shown on pirate bug predators (Heteroptera: Anthocoridae) (Pereira *et al* 2014). However, sublethal effects are often unpredictable and may hamper the growth of the natural enemy populations (Desneux *et al* 2007, Arnò & Gabarra 2011, Biondi *et al* 2013b). Consequently, the use of “selective” insecticides should be minimized and their application possibly avoided during the early phase of establishment of mirid predators in the crop. It is also important to consider that the toxicity of a specific insecticide may change according to the beneficial species, even if these species are phylogenetically and ecologically very similar as demonstrated for *N. tenuis* and *M. pygmaeus* (Arnò & Gabarra 2011). Consequently, the insecticide choice should be based on the predator species inoculated into tomato greenhouses or on the relative abundance of each species in the agroecosystem that contributes to biological control in tomato crops.

Less information is available on the toxicity of pesticides to the parasitoids of *T. absoluta*, but the studies so far published point out a higher susceptibility of these antagonists in respect to predatory bugs. Compounds that are in some way compatible with the exploitation of mirid predators (i.e., spinosad, azadirachtin) may hamper dramatically the activity of *Bracon nigricans* Szépligeti, a larval parasitoid that adapted to *T. absoluta* in the Mediterranean region (Biondi *et al* 2013a, b, Abbes *et al* 2015). Spinosad resulted very toxic to hymenopterans in general (Biondi *et al* 2012) and to predatory wasps that are important biocontrol agents of

T. absoluta in Brazil (Barros et al 2015, Bacci et al 2018); this compound is also incompatible with augmentative release of *T. acheae* (Fontes et al 2018). In other words, the application of insecticides appears much more difficult to be integrated into an IPM strategy of tomato pests exploiting the activity of parasitoids in addition to that of predators. Nonetheless, knowledge on the potential risks posed by insecticides to parasitoids of *T. absoluta* is still poor: for example, no information is available on *N. tutae*, the most active parasitoid of *T. absoluta* in the Mediterranean region.

A thorough assessment of the lethal and sublethal effects of insecticides having different modes of action on the natural enemies that play a key role in the biological control of *T. absoluta* is a research priority in order to plan insecticide resistance management (IRM) strategies characterized by negligible effects on beneficial species. For example, the evidence that insecticides of the diamides group (i.e., chlorantraniliprole and cyantraniliprole) are only slightly toxic to both predators and parasitoids (Martinou et al 2014, Pereira et al 2014, Abbes et al 2015, Fontes et al 2018) suggests that these compounds could be profitably integrated in a IPM strategy that rely on the activity of natural enemies of *T. absoluta*. Unfortunately, the selectivity of chlorantraniliprole results now to be less exploitable in many places of the Mediterranean region (i.e., Italy, Greece, and Israel) where populations of *T. absoluta* resistant to this compound are now widespread following its indiscriminate use during the first years of invasion (Roditakis et al 2018). Conversely, populations of *T. absoluta* resistant to chlorantraniliprole are still unrecorded in contexts where IPM strategies were immediately set up after the invasion of *T. absoluta* (i.e., Spain); in these areas, chlorantraniliprole may be an effective weapon to be exploited within IPM in situations where other tactics do not allow a satisfactory control of *T. absoluta*. This example points out the necessity to deepen the knowledge on the side effects of insecticides so that they can advantageously be introduced in a long-term IPM strategy capable of controlling *T. absoluta* (and other pests) and maintaining the insecticide effectiveness over time. This is particularly important in open field tomato crops where control means alternative to insecticides, largely used in greenhouse tomato (e.g., augmentation of mirid predators and egg parasitoids, insect-proof nets, mating disruption), are hardly applicable. In these contexts, the conservation of natural populations of predators and parasitoids becomes a key factor for a long-term sustainability and effectiveness of IPM strategies.

Another important component of the IPM strategy to control *T. absoluta* in the Mediterranean region is the use of *Bacillus thuringiensis*-based insecticides. These products, already used before the invasion of the tomato pinborer against the noctuid species commonly found on tomato, are fairly effective in controlling *T. absoluta*, especially when their use is implemented as part of a strategy that

incorporates biocontrol agents and/or rotation with chemical insecticide applications (González-Cabrera et al 2011, Mollà et al 2011). *Bacillus thuringiensis* toxins are highly specific (Bravo et al 2011) and their commercial formulations have resulted to be selective to predators and parasitoids of *T. absoluta* (Biondi et al 2013b). Consequently, its application is particularly advantageous during the initial phase of establishment of the natural enemies in the crop. The application of *B. thuringiensis* is also absolutely compatible with the harvesting as toxic residues do not accumulate in the fruit. The mode of action of *B. thuringiensis* is different from that of other insecticides potentially effective to *T. absoluta*, so that its use is fundamental for IRM. However, it should be noted that resistance toward *B. thuringiensis* toxins may also occur (de Almeida Melo et al 2014). The use of different *B. thuringiensis* strains (that express different toxins) and rotation with other chemical compounds with different mode of action helps to manage insecticide resistance. However, IRM must rely not only on the alternate use of compounds with different modes of action but also on reducing the number of insecticide applications which is only feasible by promoting effective biological control of *T. absoluta* by augmentation and/or conservation of natural enemies.

The availability of other microbiological insecticides could be advantageous for IPM of *T. absoluta* and for IRM. Species-specific nucleopolyhedrovirus (NPV) for controlling lepidopteran worms (e.g., *Spodoptera littoralis* NPV and *Helicoverpa armigera* NPV) is available on the European market (van Lenteren et al 2018a). Unfortunately, entomoviruses effective against *T. absoluta* are not yet available. Recently, granuloviruses isolated from *T. absoluta* (TuabGV) and *Phthorimaea operculella* (Zell.) (PhopGV) showed promising results against the larvae of *T. absoluta* (Schmitz 2016, Dapp 2017, Gómez Valderrama et al 2018) suggesting a possible future exploitation within IPM protocols.

Entomopathogenic fungi are used as a component of IPM in controlling pests such as thrips and whitefly (van Lenteren et al 2018a), especially in tomato greenhouses. Among these, commercial strains of *Beauveria bassiana* (Bals.-Criv.) Vuill. have shown epiphytic and endophytic activity against *T. absoluta* (Allegrucci et al 2011, Klieber & Reineke 2015). From this perspective, the use of mycoinsecticide applications could be considered as an additional tool in reducing chemical inputs, protecting natural enemies, and implementing IRM. In this context, the selection of new entomopathogen strains showing greater activity against *T. absoluta* is of considerable interest (Borgi et al 2016).

Another alternative to conventional chemical insecticides is represented by plant-derived compounds increasingly proposed as tools for pest and pathogen control (Isman 2006, 2015). Among these, essential oils resulted to be very promising as bioinsecticides due to their low environmental

impact (high biodegradability, low toxicity to vertebrate animals) and multiple modes of action associated to the presence of different active ingredients that hinders the development of resistance in the target pest (Isman 2000, Pavela & Benelli 2016). Essential oils of different botanical origins have shown insecticidal activity (by contact and fumigant toxicity) against *T. absoluta* in the laboratory (Umpiérrez *et al* 2012, Bouayad Alam *et al* 2017, Goudarzvande Chegini & Abbasipour 2017, Goudarzvande Chegini *et al* 2018), but their effectiveness in the field still needs to be fully investigated. The major drawbacks of field application of essential oils are related to their volatility, low persistence, poor water solubility, and possible phytotoxicity (Isman 2000, Moretti *et al* 2002). Nanoencapsulation may help in solving most of these problems (Werdin González *et al* 2014, Athanassiou *et al* 2018). In a recent laboratory study on tomato plants, Campolo *et al* (2017) found that citrus essential oils have a consistent insecticidal activity against *T. absoluta*; comparing emulsions with nanoformulations of the same citrus essential oils, the authors found a higher mortality of eggs and larvae after the contact with emulsions while the nanoformulations showed higher ingestion toxicity on larvae and lower toxicity for tomato plants. For the inclusion of citrus (or other) essential oils into IPM of *T. absoluta*, it will be necessary to evaluate their efficacy in the field and the side effects on beneficial arthropods. This is important in the light of the authorization in Europe of insecticidal formulations based on orange essential oils (Prev-Am®) for controlling sucking insects and some pathogens of many crops, including tomato, whose application could favor or disadvantage (in the case of toxic effect to predators and parasitoids) the management of *T. absoluta*. The very few studies on the side effects of essential oils on natural enemies showed slight acute toxicity and no sublethal toxicity to hymenopteran parasitoids, including *B. hebetor*, a larval parasitoid of *T. absoluta* (Biondi *et al* 2013b).

Conclusions

After an initial phase of exclusive use of chemical insecticides, the management strategies of *T. absoluta* in tomato crops in the Mediterranean region shifted in the last years toward a greater sustainability. The greatest progress occurred for greenhouse tomato crops, especially in southern Europe, with the adoption of IPM strategies based on the exploitation of generalist mirid predators that are able to control *T. absoluta* and at the same time other key pests (Perez-Hedo *et al* 2017, Roditakis *et al* 2018). Augmentation of mirid predators is generally highly effective where greenhouses are technically suitable to be screened with insect-proof nets. In this context, the integration of mirid augmentation with other biocontrol agents (e.g., augmentation of egg parasitoids), *B. thuringiensis* treatments, mating disruption,

selective chemical insecticides, and the growth of tomato varieties resistant to insect-borne viruses allows the effective control of *T. absoluta* and other tomato pests, reducing the number of chemical insecticide applications and the probability of selecting resistant populations. This strategy is often not effective in unscreened greenhouses and in the presence of large populations of *T. absoluta* able to colonize the protected crop continuously from the outside. The improvement of greenhouse structures to guarantee good ventilation and climatic regulation, even when insect-proof nets are set up, is a key factor for implementing IPM in Mediterranean tomato greenhouses.

The role of natural populations of mirid predators and, in some contexts, of parasitoids in achieving an effective control of *T. absoluta* is increasingly evident in the Mediterranean region (Arnó *et al* 2009, Perdiki *et al* 2011, Balzan & Moonen 2014, Balzan *et al* 2016a, b, Arnó *et al* 2018). A key factor is the management of the natural vegetation surrounding the cultivated fields and the introduction of companion plants in order to facilitate the persistence of natural enemies in the agroecosystem and their colonization of the crops. This is pivotal for IPM in tomato unscreened greenhouses and even more for open field crops, with the availability of low-impact control tactics (i.e., alternatives to chemical insecticides) being particularly limited in these situations. Although increased plant biodiversity results frequently in complex communities of natural enemies, better control of *T. absoluta*, and increased productivity in tomato crops, this cannot be considered an obvious result. Field research is still needed to understand the interactions among *T. absoluta*, natural enemies, tomato crop, and surrounding vegetation in order to identify the assemblage of plant species that, in each cultivation area, favors the effective control of *T. absoluta* (and other pests) by natural enemies, contributes to increase crop yields, and prevents negative effects on the crop (e.g., limiting tomato plant feeding by mirid predators, not hosting key pests or plant pathogens like viruses).

The efficiency of natural enemies must not be hampered by wide spectrum insecticides which generally show acute and/or sublethal toxicity to them (Desneux *et al* 2007). Unfortunately, few active ingredients with different modes of action are available in Europe that can effectively control *T. absoluta*, and there is an increasing frequency of resistant populations in the Mediterranean region (Roditakis *et al* 2018). A direct consequence will be a reduction of effectiveness of these compounds over time. Among them, only a few showed a certain selectivity to mirid predators and even less to parasitoids (Arnó & Gabarra 2011, Mollà *et al* 2011, Biondi *et al* 2013b, Martinou *et al* 2014, Fontes *et al* 2018). Consequently, where the exploitation of natural enemies' conservation is combined with the use of chemical insecticides, difficulties in the management of insecticide resistance can arise. This can happen especially because, except for

B. thuringiensis-based insecticides, other control strategies are unavailable, as for example in open field tomato crops.

The efficacy of IPM strategies that are consolidating in southern Europe over time could only rely on the availability of additional selective insecticides. The research must be directed to select new active ingredients characterized by different modes of action and low environmental impact. Their lethal and sublethal effects on field populations of beneficial arthropods should be carefully assessed as they should for already available compounds (Biondi et al 2018). Botanical insecticides, in particular essential oils, appear promising and efforts should be done to produce formulations that maximize the toxic effect on *T. absoluta* and reduce unwanted side effects on beneficial arthropods and cultivated plants (Biondi et al 2013b, Campolo et al 2017). Similarly, new microbiological insecticides (e.g., granuloviruses) can be of great help in countering the onset of insecticide resistance in *T. absoluta* populations and facilitating conservation biological control.

Finally, additional studies should be undertaken to optimize the application of pheromone-based control, in particular mating disruption which is ensuring appreciable results as a component of *T. absoluta* IPM in unscreened greenhouses, especially when applied at a large scale.

For a long-lasting sustainable management of *T. absoluta*, the development of resistant varieties is also a key factor (Biondi et al 2018), particularly in open field cultivation of processing tomato, for which IPM is based on insecticide applications and conservation biological control. In this context, tomato plants expressing both direct and indirect defense mechanisms, after induction by insect feeding (Proffitt et al 2011, De Backer et al 2017, Anastasaki et al 2018), are of particular interest to exploit a strategy that pushes the pest (i.e., *T. absoluta*) away from and pulls natural enemies (i.e., mirid predators) in the cultivated field (Khan et al 2008).

In conclusion, the management of *T. absoluta* has reached a good level of sustainability in southern Europe, especially in greenhouse tomato. However, the risk of a loss of effectiveness of current strategies is considerable in relation to the possible development of resistance to the few available insecticides which still represent a fundamental weapon in many context, in particular for open field crops. The development of new control means and conservation strategies that promote an effective activity of natural enemies at the crop level is essential to improve and maintain over time the effectiveness and sustainability of *T. absoluta* management.

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Compliance with Ethical Standards

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

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