Tomato leafminer (*Tuta absoluta*): impacts and coping strategies for Africa

Evidence Note (March 2019)

KNOWLEDGE FOR LIFE

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Executive summary

Background

Since its first arrival on the African continent in 2008, the tomato leafminer, *Tuta absoluta*, remains the most important biotic constraint to tomato production in North and sub-Saharan Africa. Subsequently, several research efforts have been undertaken to understand the bio-ecology of *Tuta absoluta* and to develop integrated pest management (IPM) technologies to cope with this pest. This evidence note therefore provides information on the key facts about *Tuta absoluta*, and data on how farmers are coping with the pest in Kenya and Zambia, summarizes the research and development on control methods, and makes recommendations for sustainable management of the pest. This information will be useful for a wide range of stakeholders, including researchers, policy makers, donors and other high-level decision makers.

Strategic importance of tomato

Tomato (*Solanum lycopercicum L.*) is the most consumed fruit in Africa, both in its raw and processed forms, and its production has a particular socio-economic significance, as it particularly offers employment opportunities to women, who contribute to over 60% of the labour force. The estimated annual global production in 2017 was 182 million tonnes (21 million tonnes in Africa), and tomato is the sixth most valuable cultivated crop, worth US$ 87.9 billion in 2016 alone. In Africa, total production amounts to 37.8 million tonnes annually, with the biggest producers being Egypt, Nigeria, Tunisia and Morocco. Nigeria, is sub-Saharan Africa’s biggest producer of tomatoes, producing up to 1.5 million tonnes of tomatoes annually. However, the continent does not produce enough tomatoes to meet its own needs.

Tuta absoluta biology and yield loss

The likely origin of *T. absoluta* is reported to be South America, from where it spread to Spain in 2006, and to Africa via Algeria, Morocco and Tunisia one year later, in 2007. Much information on the biology of *Tuta absoluta* suggests that the primary host is tomato, although the pest can feed and develop on other members of the Solanaceae family. The feeding habits of *Tuta absoluta* make its presence difficult to detect in the early infestation period, resulting in severe damage to young plants. *Tuta absoluta* infestation results in significant yield losses of tomato and other crops, including reduction in crop quality. Losses affect the farmer’s income directly due to reduction in marketable yield and indirectly through higher production costs, a consequence of increased investment in pest management. The consumer will be affected by the increased price of commodities due to the higher production cost incurred by the farmer, and potential long-term effects when pesticides are not properly used, albeit this is not yet well documented. Yield losses are variable and normally range from 11% to 43%, but can reach as high as 100% in some locations, as a result of both the direct and indirect damage.

Spread of *Tuta absoluta* in Africa, the Middle East and Asia

First reported in North Africa in 2007, *Tuta absoluta* has spread at an average speed of 800 km per year both eastward and southward to increasing numbers of sub-Saharan countries, where it has become a major pest of tomato and other Solanaceae. It has since invaded 41 of the 54 African countries. During the last 10 years, *Tuta absoluta* has also spread in the Middle East and Asia, including India, Iran, Israel, Syria and Turkey. Large areas of Asia are highly suitable for *Tuta absoluta*, some corresponding with the major tomato-producing zones. The pest can be expected to spread rapidly through Asia, so countries not yet invaded should prepare response plans immediately. Species distribution models have predicted suitable conditions exist in Central America and the southern USA, southern Europe and North Africa. The Arabian Peninsula, India, a strip of Africa below the Sahara, and East Africa are also highly suitable.

Impacts of *Tuta absoluta* in Kenya and Zambia

Impacts of *Tuta absoluta* were estimated for Kenya and Zambia during a household survey conducted in 2018. The study showed that between 97.9% and 99% of farmers reported *Tuta absoluta* as a problem in their tomato fields in both countries. The study further shows that farmers in Kenya had lived with *Tuta absoluta* longer than the farmers in Zambia, which is not surprising as the pest was reported in Kenya first, before Zambia. Infestation rates were reported to be lower in Kenya than Zambia, with most farmers in Kenya (53%) reporting a minor part of the crop to be infested, while in Zambia about 50% reported a major part or the entire area of their tomato crop to be affected. On average, the majority of farmers in Zambia (57%) indicated they had lost a big proportion of their crop to *Tuta absoluta*, compared to a 41% reporting this in Kenya. The mean seasonal production loss due to *Tuta absoluta* was estimated to be at least 114,000 tonnes for Kenya and 10,700 tonnes for Zambia. This translates to US$ 59.3 million, and US$ 8.7 million in economic losses for Kenya and Zambia, respectively. Estimates for 12 selected countries taken together suggest that the impact of *Tuta absoluta* on sub-Saharan Africa tomato production is at least 1.05 million tonnes lost annually, out of the total expected production of 3.64 million tonnes, with losses of at least US$ 791.5 million annually, of the total expected value of US$ 2,737 million. However, the figures are based on farmer responses and could likely be an over-estimate, thus more specific field research studies are recommended to determine economic losses under no control, and with the currently used farmer practices.

Coping strategies against *Tuta absoluta*

Use of pesticides was the predominant method deployed by farmers to control the pest in both countries in the study, with 96.5% of farmers in Kenya using this method, and 97.6% of farmers in Zambia. However, only 27.2% and 17.2% of farmers in Kenya and Zambia, respectively, indicated pesticide treatments as being very successful. About 6.4% of farmers used highly hazardous pesticides, with up to three such products recorded in Zambia and one product in Kenya. In Kenya, the majority of farmers applied between one and five insecticide sprays (73.1%), while in Zambia, the majority of farmers applied between six and 10 insecticide sprays (33.9%) per season. In Kenya, the average amount spent on pesticides per household amounted to Kenyan Shillings (KES) 4,864 (US$ 47.2), which is approximately US$ 33.7/ha, while in Zambia, the average amount spent on pesticides per household amounted to Zambia Kwacha (ZMW) 504 (US$ 42.1), approximately US$ 9.4/ha – more than threefold cheaper than Kenya. When we consider cost/spray, the average farmer in Kenya spent KES 1250 (US$ 12.3), compared to Zambia, where each spray cost ZMW 43 (US$ 4.2). In terms of pesticide safety, 34.8% of farmers in Kenya and 38.3% in Zambia did not use any personal protective equipment. Skin itching was among the most frequently reported side effect of pesticide use, with 30.6% of farmers in Kenya and 24.8% in Zambia reporting this symptom.

Trade impacts

Tuta absoluta is recommended for regulation as a quarantine pest in the European Union (EU), and exporting countries may be required to apply mandatory phytosanitary procedures, which results in extra cost to exporters and the national plant protection organization. However, in general, the number of interceptions of commodities with *Tuta absoluta* globally that enter the EU remains low. Within the five-year period from 2013 to 2017, there was only one interception in the EU of *Tuta absoluta*, on tomato originating from Morocco in 2015. However, in 2018, interceptions of commodities with *Tuta absoluta* saw a sharp increase. For instance, from Africa alone, there were 12 interceptions on *S. lycopercicum*, and one on wood packaging material from Tunisia. Other countries with interceptions include Albania (1) and Lebanon (1). This level of interceptions, over a long period of time, suggests that countries are managing *Tuta absoluta* well and are taking all the necessary precautions

Controlling Tuta absoluta

Detection, correct identification (of pest and damage) and the use of threshold levels are key in the control of this pest. Several approaches have been used for monitoring and controlling *Tuta absoluta*, in both the native and exotic ranges of the pest. The methods currently being used in Africa, as identified by the household survey conducted in 2018, include pesticides, pheromone traps, destroying infected plants, staking, organic pesticide and crushing larvae. Other methods known to be effective against *Tuta absoluta* are highlighted in Section 4 of this evidence note, and include mating disruption, microbial pesticides, botanicals, netting technology, biocontrol and IPM strategies.

Tuta absoluta advice and information

According to the aforementioned household survey, neighbours, friends and family are the main sources of information and advice on *Tuta absoluta* (34.5% in Kenya; 41.8% in Zambia). Many farmers also obtain information from agro-dealers and input suppliers (30.8% in Kenya; 22.8% in Zambia). In Zambia, government extension workers continue to play an important role in information dissemination (40.4%). Plant clinics remain an important as a source of information in Kenya (15.5%), but less so in Zambia (3.1%). Across both countries, there is still a low uptake of e-extension services, using SMS and smartphones (>1% of respondents) or internet (between 1.2% and 3.8%). CABI launched a *Tuta absoluta* Portal (https://www.cabi.org/ISC/tuta) as an integral part of the open access Invasive Species Compendium. The portal includes a wide variety of information for farmers, policy makers, researchers and other stakeholders, collated from multiple sources

Recommendations

Recognizing that *Tuta absoluta* is already present in most of Africa, and noting that in the absence of effective alternative management options, smallholder growers will continue to use broad-spectrum insecticides, the following recommendations are proposed to a wide range of stakeholders.

High-level policy makers:

- make informed, science-based decisions at national level to protect biodiversity, consumers and trade from indiscriminate pesticide use
- conduct a study on the health and environmental impacts of the high pesticide use on tomatoes to the country
- develop a technical guidance standard for pesticides use in tomato: covering procurement, risk reduction and resistance management
- lobby for budgetary allocation from national governments to subsidize the cost of low-risk options for managing *Tuta absoluta*

- provide incentives to industry associations that are involved in the production and sale of lower-risk products for *Tuta absoluta*

Regulators:

- officially report to the International Plant Protection Convention if the pest is already present within the borders of the country
- identify unregistered and/or highly hazardous products being used for *Tuta absoluta* and regulate their distribution and use
- facilitate the registration and promotion of lower-risk products for *Tuta absoluta*, including biopesticides, botanicals, pheromones, and the use of natural enemies through augmentative biological control
- explore with research agencies the use of classical biological control for *Tuta absoluta* using host-specific parasitoids from South America

Researchers:

- carry out rapid testing of new active ingredients of pesticides for their modes of action and low environmental impact, including lethal and sub-lethal effects on field populations of beneficial arthropods, recognizing that farmers will continue to use such products in the foreseeable future
- test locally available biopesticides and botanicals, particularly essential oils and produce formulations that maximize the toxic effect on *Tuta absoluta* and reduce side effects on beneficial arthropods
- carry out surveys to identify local natural enemies that can be used in augmentative biological control, such as predatory mirid bugs and *Trichogramma spp*. egg parasitoids, which have been successfully used elsewhere
- establish the economic considerations for control methods such as augmentation and the use of conservation biological control
- exploit methods such as companion plants to improve the conservation and the effectiveness of predators and parasitoids; augmentation of parasitoids; and mating disruption
- test a model for the sustainable production of biological agents at community level

Advisory services:

- communicate to farmers, using various communication approaches, about the negative impacts of indiscriminate pesticide use on their health and the environment
- consider efficacy, safety, sustainability, practicality, availability and cost-effectiveness when recommending control practices
- encourage farmers to integrate highly selective low-risk pest control products with biological control within a holistic IPM strategy
- scale out pheromone-based monitoring for management of *Tuta absoluta*, rather than the spray programme currently practised at the farm level

Smallholder farmers;

- carry out pest monitoring to determine the threshold levels either for the timing of control, or for making a decision on whether or not remedial action is to be taken. A spray regime based on a programme is not recommended
- use only pesticides recommended by the government, and choose those that are lower-risk or selective insecticides if available/affordable, to protect mirid predators

- use proper personal protective equipment (PPE) when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product
- consider using homemade products made from plants known to have pesticidal effect
- adapt specific cultural practices that conserve native natural enemies
- use short duration varieties whenever appropriate

Commercial farmers:

- the spray regime for pesticides should be based on an action threshold that takes into consideration the expected value of the crop, the expected loss if untreated, and the cost of treatment
- farm workers should use the proper PPE when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product
- assess the efficacy of other lower-risk products, if available, and adopt for use
- augment predatory mirids in tomato greenhouses using commercial forms of the product where they are commercially available
- maintain good records of agronomy, monitoring, interventions, yield etc, and review regularly to determine the cost benefit of the control methods used

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Acronyms

AEZ	Agro-ecological zone
CABI	CAB International
EIL	Economic injury level
EPPO	European Plant Protection Organisation
ETL	Economic threshold level
FAOSTAT	FAO Statistical Database
KES	Kenya Shillings
PMDG	Pest Management Decision Guide
PPE	Personal protective equipment
SIT	Sterile insect technique
ZMW	Zambia Kwacha

Introduction

Tomato (*Solanum lycopercicum L*.) is among the most economically important vegetables globally, with an estimated annual production of 182 million tonnes, worth an estimated US$ 87.9 billion. In Africa, tomato cultivation has a particular socio-economic significance as it particularly offers employment opportunities to women, who contribute to over 60% of the labour force along the value chain. Furthermore, tomato provides much needed vitamins, minerals and essential amino acids to impoverished rural communities. Despite its socio-economic significance, tomato production is constrained by numerous biotic and abiotic factors. Among the former are arthropod pests, of which the tomato leaf miner, *Tuta absoluta* (Meyrick), is currently the most serious pest to this crop.

To manage the pest, growers resort to use of broad-spectrum insecticides. However, this practice is unsustainable and likely to lead to widespread development of resistance, contamination of the fruits due to high pesticide residues, and human and environmental health hazards due to over-reliance on chemical pesticides. In South America, extensive use of synthetic insecticides led to the development of resistance to all classes of insecticides and this is likely to be the case in Africa unless a sound integrated pest management (IPM) approach is implemented.

In view of the threat posed by this pest, this evidence note aims to provide evidence and recommendations for decision makers in Africa responsible for the response to the pest, as well as for external organizations seeking to assist in management. This information will be useful for decision makers to prioritize investment and interventions in responding to the continuing threat. This evidence note is structured into six sections as follows:

- in **Section 1** we briefly review tomato production trends, the *Tuta absoluta* problem, current distribution of the pest, and its environmental suitability
- in **Section 2** we synthesize the results of farmer surveys conducted in Kenya and Zambia in 2018, highlighting how farmers are coping with the pest; using loss data we also extrapolate national tomato yield losses for selected countries
- in **Section 3** we provide information on control methods currently deployed for the management of *Tuta absoluta*, highlighting significant new findings
- in **Section 4** we highlight the communication aspects related to *Tuta absoluta* control, and the criteria for advice that should be given to the farmer
- in **Section 5** we conclude with some recommendations for key stakeholder groups

1. Tomato production and the *Tuta absoluta* problem

1.1 Commodity context

Tomato (*Solanum lycopercicum L.*) is Africa's most consumed fruit (or vegetable), eaten by millions of people across the continent's diverse religious, ethnic and social groups. Both in the raw and processed forms, tomatoes are central to most African diets. At the global scale, tomato is among the most economically important vegetables, with an estimated annual global production of 182 million tonnes (21 million tonnes in Africa) in 2017, and it is ranked as the sixth most valuable cultivated crop, worth US$ 87.9 billion in 2016. In Africa alone, total production amounts to 37.8 million tonnes annually (FAO Statistical Database (FAOSTAT), 2017).

The biggest producers of the crop on the continent include Egypt, Nigeria, Tunisia and Morocco. Tomato is the second most important horticultural export crop of Tunisia, with 13% of the export targeted at the EU market. The area under tomato production in the country is 32,000 ha, with an annual production of more than 1 million tonnes (FAOSTAT, 2017). Nigeria is sub-Saharan Africa's biggest producer of tomatoes, producing up to 1.5 million tonnes of tomatoes every year, making it the 14th largest producer of tomatoes in the world. Average yields as low as 7 tonnes/ha have been reported from Tanzania and 10 tonnes/ha from Uganda, while yields as high as 100 tonnes/ha have been recorded from commercial farmers in Zimbabwe. In all of Africa, tomato cultivation has a particular socio-economic significance as it particularly offers employment opportunities to women, who contribute to over 60% of the labour force along the value chain (Villareal, 1980). In Kenya, South Sudan and Uganda, tomato also constitutes a major home garden commodity for consumption, as well as for domestic and regional markets, and commercial production is on the increase (USAID, 2005). Furthermore, tomato provides much needed vitamins and minerals to impoverished rural communities (Villareal, 1980; USAID, 2005).

The current population of Africa is 1.3 billion people, and with a current growth rate of 2.5% per year, Africa has the world's fastest growing population, with the number of inhabitants expected to reach 2.5 billion by 2050. However, the African continent does not produce enough tomatoes to meet its own needs. With an annual expenditure of US$ 645 million in imports of tomato and related products (FAOSTAT, 2016), this puts a burden on the foreign exchange of the continent. Almost every country in Africa consumes more tomatoes than it produces. The rest is imported from outside the continent, especially from China, the world's biggest exporter of tomato products. Nigeria, despite its status as a leading producer, still spends up to $500 million annually to import tomato products (especially purees, pastes and canned tomatoes), making Nigeria one of the biggest importers of tomato paste in the world.

1.2 The tomato leaf miner, *Tuta absoluta*

Native to Peru in South America, the tomato leaf miner *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), also named the South American tomato pinworm, has gained notoriety as the most important and devastating pest of tomato wherever it has invaded (Figure 1). Infestation by the pest causes yield losses of up to 100% on tomato, although the pest also attacks other Solanaceae. Outside of its native range, *Tuta absoluta* was first observed in Spain in 2006, from where it has spread to different parts of the world, often becoming a serious threat to tomato production industry wherever it invades. It was first reported on the African continent in Algeria, Morocco and Tunisia in 2007, and has since invaded 41 of the 54 African countries. Considering *Tuta absoluta*'s high biotic potential, its ability to adapt to various climatic conditions and the speed with which it has colonized Africa, the invasion has impacted heavily on the livelihood of local tomato growers and tomato agribusinesses.

Figure 1: Adult *Tuta absoluta* and mining damage on tomato leaf

1.3 *Tuta absoluta* bio-ecology and damage

Three recent reviews on this pest for the Afro-Eurasian region (Biondi *et al.*, 2018), Mediterranean Basin (Giorgini *et al.*, 2018) and Africa (Mansour *et al.*, 2018) have provided extensive information on the biology and ecology of *Tuta absoluta* and its worldwide spread. *Tuta absoluta*'s primary host is tomato, though it can feed and develop on other members of the Solanaceae. Feeding damage is caused when the larvae penetrate the leaf and feed on the mesophyll parts of leaves. This results in irregular mines on the leaf surface, negatively affecting the photosynthetic capacity of the plant (Figure 2). Subsequently, damaged leaves shrivel, decreasing the photosynthetic capacity of the plant and potentially decreasing the plant's ability to defend itself from other harmful agents. The galleries and mines in the leaves alter the general development of the plant and can cause necrosis (Biondi *et al.*, 2018). Under severe attacks, the leaves have a burnt appearance. Other common signs and symptoms of *Tuta absoluta* damage include: puncture marks, abnormal shape, exit holes, rot due to secondary infective agents, and frass (fine powdery material that plant-eating insects pass as waste after they digest plant parts). Mature larvae (third to four instar) can feed on all parts of the plant. This results in significant damage to the plant.

Figure 2: *Tuta absoluta* damage on tomato leaves

The larvae, at high densities, will bore into the stem and fruits (Figures 3 and 4). The pest also feeds directly on the growing tip of the plant. This kills and/or halts the development of the plant, directly compromising the yield of the crop (Desneux *et al*., 2010; Campos *et al*., 2017). Indirect damage also happens as a result of larvae feeding. The mines and galleries in the stems and fruits are entry routes for secondary infection by pathogens, further increasing the damage and cost of control, and lowering the market value of the fruits (EPPO, 2005; Tropea Garzia *et al*., 2012; Campos *et al*., 2017).

1.4 Yield losses due to Tuta absoluta

Yield losses of up to 50–100% have been reported (Desneux *et al*., 2010) as a result of the direct and indirect damage. In Ethiopia, the yield loss due to *Tuta absoluta* was reported by one study to be in the range of 60.08% to 82.31% (Shiberu and Getu, 2017), while in Tunisia, Chermiti *et al.* (2009) estimated losses ranging from 11% to 43%, and as high as 100% in some locations in Egypt (Moussa *et al*., 2013). In Sudan, fruit damage was reported to range between 80% and 100% in most open field tomato crops (Mohamed *et al*., 2012). In Angola, damage to open field tomato crops was reported to range from 84% to 100% (Chidege *et al*., 2017). In Zambia, about 90% of crop damage has been reported, and yields are reduced to zero within three weeks of infestation without insecticide treatments (Luangala *et al*., 2016). In Tanzania, the mean plant damage inflicted by the pest in all tomato fields was reported to be between 90% and 100% (Chidege *et al*., 2016). In 2015, the Nigerian government declared an emergency after *Tuta absoluta* destroyed more than 80% of the tomato fields in the region, causing a 20-fold increase in the tomato price (FAO, 2015; Borisade *et al*., 2017). Since its detection outside of its native ranges in 2006 and subsequent spread and invasion, 21.5% of surface cultivated (0.95 million ha) and 27.2% of tomato production (41 million tonnes) had been infested by *Tuta absoluta* by 2011 (Desneux *et al*., 2011). Consequently, a rise in tomato prices and an increase in synthetic pesticide applications have been observed in several countries, leading to increased tomato production costs. There is every indication that *Tuta absoluta* will continue to impact heavily on the livelihood of local tomato growers and tomato agribusinesses in affected regions. In Africa particularly, the long-term health effects of pesticide use are likely to be felt and studies are needed to provide data that might be used in decision making on safer ways to manage this pest.

Figure 3: Pesticide residues from spraying against *Tuta absoluta* damage

Figure 4: Pesticide residues on tomato fruit from spraying against *Tuta absoluta* damage

1.5 Origin, pathways of entry and establishment

Evidence from molecular studies on the invasion pathway of *Tuta absoluta* suggests that central Chile is likely the origin of the introduction of *Tuta absoluta* in Europe (Guillemaud *et al*., 2015). In its native ranges, the species expanded its range and established itself in other regions and countries of Latin America between the 1960s and 1980s. These countries were Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Panama, Paraguay, Peru, Uruguay and Venezuela (Campos *et al*., 2017). The first record of *Tuta absoluta* outside neotropical America was in Spain in 2006 (Desneux *et al*., 2011), from where it spread to other Mediterranean countries and has established itself in Asia and countries in sub-Saharan Africa (Al-Jboory *et al*., 2012; Brévault *et al*., 2014; Diarra, 2014; Esenali *et al*., 2017; Seplyarsky *et al*., 2010; Tumuhaise *et al*., 2016).

Tuta absoluta has been introduced to several exotic ranges, where it has become invasive, threatening the production of tomato (Campos *et al*., 2017); this includes major tomato producers, i.e. India, Turkey, Egypt, Iran, Italy and Spain (EPPO, 2018). Different pathways are involved in facilitating the entry and spread of *Tuta absoluta* in the invaded ranges. Agricultural trade of tomato fruits has been cited as the main pathway in which *Tuta absoluta* has spread and expanded its ranges (Desneux *et al*., 2010). For example, agricultural trade between Chile and Argentina introduced *Tuta absoluta* to the Mendoza province (Argentina). The insect has also been found on packing and sorting equipment, e.g. in the Netherlands, and was also recorded in Russia, having arrived from tomato shipments from Spain (Potting *et al*., 2013). Planting materials which originate from countries where *Tuta absoluta* is present have been reported to introduce infestation in non-invaded ranges (Karadjova *et al*., 2013).

Importation of tomato fruits is one major pathway for entry of *Tuta absoluta* in several countries over long distances and since the insect is an internal feeder, early infestations can go unnoticed (Karadjova *et al*., 2013). This can then go on to become the first infestation source, contributing to the risk of future outbreaks (Desneux *et al*., 2010; Potting *et al*., 2013). A major risk for short distance dispersal is the spread through natural means (flight). This was probably how the moth spread in Spain (Desneux *et al*., 2010; Potting *et al*., 2013).

Different *Tuta absoluta* stages can survive on tomato, eggplant and packaging material, including crates, boxes etc. This has contributed to risks through the introduction of insect-infested crates to new clean tomato growing places (Karadjova *et al*., 2013). Since packaging material travels across the same geographical borders as packaged fruits, spread is inevitable. Larvae and pupae can complete their life-cycle in the new areas after arrival, while the adults can fly away during the offloading period, creating more infestation risks, e.g. as recorded in UK (Sixsmith, 2010).

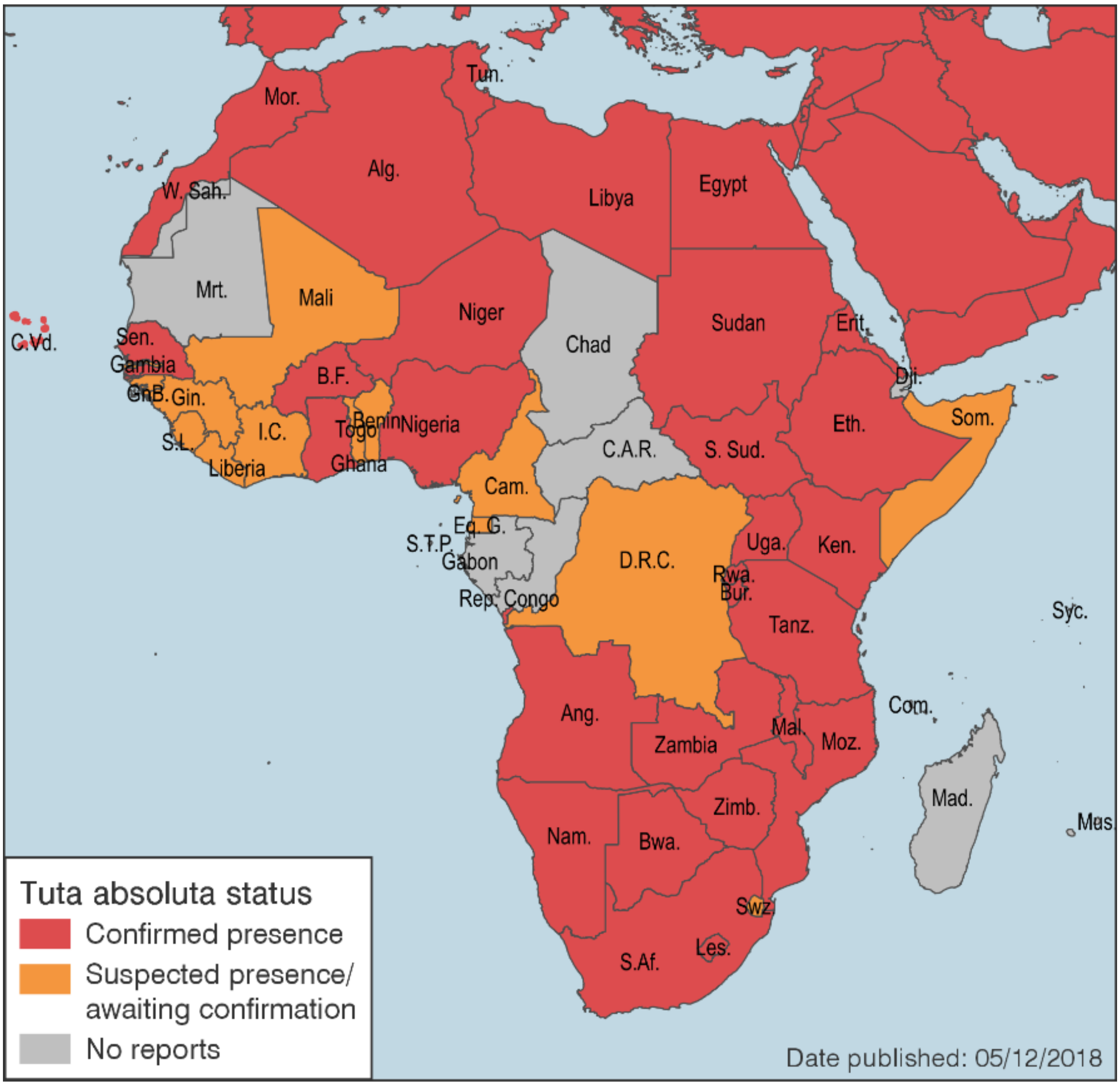
Infested transplants also form another pathway for entry of *Tuta absoluta*. The intensification of tomato production in Bulgaria (Karadjova *et al*., 2013) increased the importation of transplants from Greece; planting of infested plants through this route posed a great risk of infestation in south-central Bulgaria. Indeed, the pest is now present in Bulgaria, although with restricted distribution (EPPO, 2018).

The establishment of *Tuta absoluta* in new areas can be quite fast. For instance, following the first record in Spain (i.e. in 2006), the pest established itself in all main coastal areas of Spain and its populations reached damaging levels at multiple locations on the Mediterranean coast (Desneux *et al*., 2010). Between 2008 and 2009, *Tuta absoluta* was reported to be established in tomato crops from Italy, southern France, Greece, Portugal, Morocco, Algeria and Tunisia (Potting *et al*., 2013). *Tuta absoluta* has also been reported in cooler parts of Europe (e.g. Switzerland, the UK, Germany and the Netherlands), though this has been restricted to protected tomato cultivation (Potting *et al*., 2013). Some years later, *Tuta absoluta* is now established outdoors in all countries around the Mediterranean Sea and in the Middle East (Desneux *et al*., 2010; Biondi *et al*., 2018, Giorgini *et al*., 2018).

1.6 Current spread and distribution of *Tuta absoluta* in Africa

Tuta absoluta has spread and expanded its ranges in Africa, with several reports confirming the presence of this pest. Figure 5 below shows the individual country status as regards *Tuta absoluta* presence (EPPO, 2018). Since the first detection in North Africa – Tunisia and Morocco – in 2008 *Tuta absoluta* has spread at an average speed of 800 km per year, both eastward and southward (Biondi *et al*., 2018, Giorgini *et al*., 2018) to other sub-Saharan countries, where it has become a major pest. Currently, *Tuta absoluta* is reported in 41 of the 54 African countries (Mansour *et al*., 2018). It was reported in West Africa – Niger and Nigeria in 2010, and Senegal in 2011; East Africa – Kenya in 2014, Tanzania in 2014 and Uganda in 2015; and southern Africa – Botswana, Zambia and South Africa in 2016 (Brévault *et al*., 2014; Chidege *et al*., 2016; 2017; Mohamed *et al*., 2012; Pfeiffer *et al*., 2013; Retta and Berhe, 2015; Tonnang *et al*., 2015; Tumuhaise *et al*., 2016; Mutamiswa *et al*., 2017; Visser *et al*., 2017; Zekeya *et al*., 2017, Mansour *et al*., 2018; Ndor, 2018). Countries with widespread distribution of *Tuta absoluta* in Africa include Egypt, Zambia, Mayotte, Tunisia, Mozambique and Morocco. The rapid spread over long distances across political borders supports the human-aided hypothesis regarding the dispersal of *Tuta absoluta* (e.g. trade of tomato fruits) and less the possibility of its being spread by natural means.

Figure 5: Countries where *Tuta absoluta* has spread in Africa



***Source**: CABI, 2018*

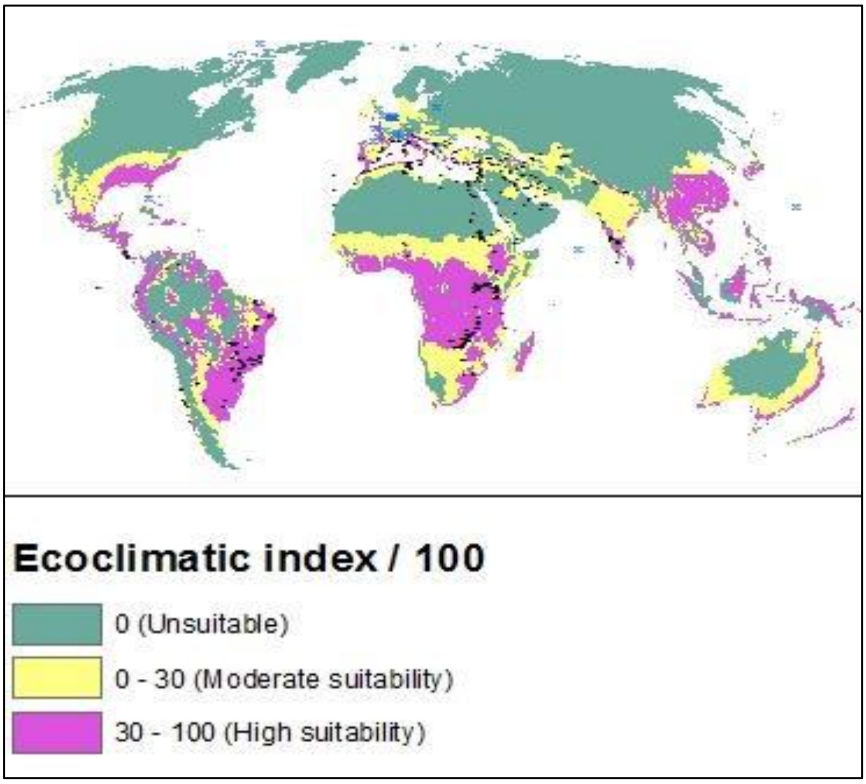
1.7 Further spread and distribution of *Tuta absoluta* in Asia

Due to the spatial continuity of vegetable cultivation across political borders, the absence/inadequate effective surveillance mechanisms, lack of/poor specific phytosanitary expertise to intercept infested vegetables, ever-growing tourism and increasing intra-continental trade, the risk of *Tuta absoluta* becoming more widespread in infested countries is high (Tonnang *et al*., 2015). Countries in the Middle East and Asia where *Tuta absoluta* has been reported include: Israel, Iraq, Jordan, Saudi Arabia, Kuwait (Abdul-Rassoul, 2014; Desneux *et al*., 2010, 2011; Esenali *et al*., 2017; Seplyarsky *et al*., 2010). In 2014, there were reports of this pest being present in India, where it was found to be infesting tomato plants in Ahmednagar, Dhule, Jalgaon, Nashik and Satara districts of Maharashtra (Shashank *et al*., 2015; 2016). *Tuta absoluta* is also reported to be present in Bangladesh (Hossain *et al*., 2016).

1.8 Environmental suitability modelling for *Tuta absoluta*

Using data collected in the field in Ghana, Uganda and Zambia, and current information on known presence of *Tuta absoluta* in the open field, improvements have been made to published pest distribution forecasts for this pest. The current environmental suitability model predicts suitable conditions exist in South and Central America, southern Europe, and parts of Australia and East Africa (Figure 6). The simulations suggest the potential worldwide spread of *Tuta absoluta* to all key tomato growing regions. Given its high biotic potential and ability to adapt to various climatic conditions, coupled with global warming, this may further favour further establishment in areas not specifically suitable in the past, increasing the importance of this tomato pest. For instance, *Tuta absoluta* moths have been trapped in some areas with few or no tomato crops, and urban environments. This suggests high mobility of moth populations and capacity to survive in harsh environments, and to persist on alternative host plants. In places with less suitable environmental factors or conditions, the year-round presence of *Tuta absoluta* hosts (including alternative hosts not from the solanaceous family) may increase the risks of invasion and spread (Guedes and Picanço, 2012; Guimapi *et al*., 2016).

Figure 6: Environmental suitability of *Tuta absoluta*.



***Source**: Regan Early, Exeter University*

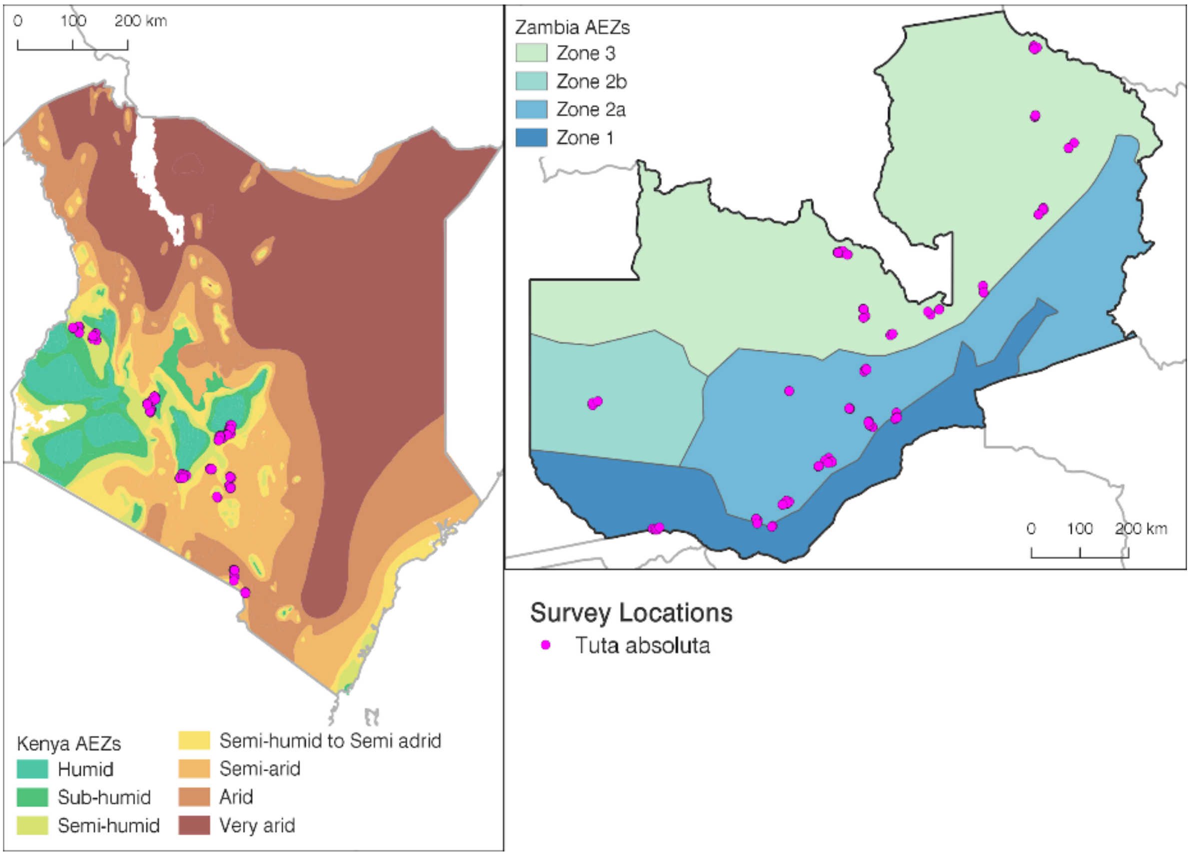
2. Impacts of *Tuta absoluta* on tomato yield and other socio-economic variables

2.1 Household survey methodology

In order to understand the impacts of *Tuta absoluta* on tomato yield and farmers' livelihoods, and to obtain data that could be extrapolated to national level, household surveys were conducted in Kenya and Zambia using an Open Data Kit data collection tool on tablets. The surveys were conducted by CABI in partnership with Kenya Agricultural Research Organization (KARLO) and the respective county governments, and the Zambia Agricultural Research Institute (ZARI). Household heads were interviewed face-to-face by 10 officers in Zambia, and six in Kenya, who were trained prior to the surveys. The survey tool captured information on household composition and farming activities, perceptions of impacts of *Tuta absoluta* on yield and control practices employed, and information resources. The sample consisted of 826 (400 in Kenya and 426 in Zambia) farm households that had grown tomato in 2017 and 2018 cropping season (Figure 7). In order to be representative of the different country agro-ecologies and production systems for tomato, the survey covered seven counties (11 sub counties) in Kenya, and seven provinces (18 districts) in Zambia. Data were collected during August–September 2018. The survey targeted the household head or spouse, or any family member who was responsible for making farming decisions.

During the household survey, we also undertook field observations for plant damage and trapping to determine the abundance of the pest in the locality. We installed traps with Tutrack lure, which contains pheromones that attract the male *Tuta absoluta* moths, to monitor the population of the pest. The traps were installed in farmers' fields at the start of interviews, and the number of moths captured was counted and recorded. The trapping duration ranged from 1 to 1.5 hours. For field observations, we followed five transects and counted 20 plants along each transect (100 plants per household), examining them for leaf and fruit damage. Field observations were aimed at obtaining actual data on pest infestation and abundance, and how this correlates with farmers' perceptions on the pest damage.

Figure 7: Map of the survey areas in Kenya and Zambia



2.2 Household characteristics

The average age of household head was 46.7 years in Kenya and 46.3 years in Zambia, suggesting that farmers who practise tomato farming are generally middle-aged (Table 1). Most respondents surveyed in both countries were male (Kenya, 91.3%; Zambia 86.6%). The majority of households practised farming as their primary activity. In terms of land holding, households in Kenya owned less land (1.4 hectares), compared to the households in Zambia (4.5 hectares).

Table 1: Household profiles of respondents in Kenya and Zambia

Variable	Kenya (n=400)	Zambia (n=426)
Age of household head (years)	46.7	46.3
Male-headed household	91.3%	86.6%
Household size (no. of people)	4.73	7.37
Education level of household head:		
None	2.2%	1.9%
Primary	25.8%	34.51%
Secondary	32.3%	50.2%
Tertiary	39.8%	13.4%
Household's primary activity is farming	85.0%	91.8%
Total land owned (hectares)	1.4	4.5

The most common pest on tomato was *Tuta absoluta*, with between 97.9% and 99% of farmers reporting it as a problem (Table 2). Other important pest and disease problems mentioned were tomato blight, whiteflies and bacterial wilt.

Table 2: Common problems reported by farmers on tomato in Kenya and Zambia

Main problem	Kenya % (n=400)	Zambia % (n=426)
Tomato leaf miner	99.0	97.9
Tomato blight	61.6	24.9
Whiteflies	50.3	27.7
Bacterial wilt	20.8	4.9
American bollworm	8.0	16.2
Aphids	8.0	9.2
Fruit flies	6.5	0.9
Blossom end rot	5.3	5.9
Liriomyza sp (leaf miners)	5.0	1.6
False codling moth	1.0	0.0
Red spider mite	0.0	18.3
Black spot	0.0	12.7
Powdery mildew	0.0	8. 5
Cutworms	0.0	6.6
Others	24.0	3.8

All farmers interviewed in both countries had previously encountered *Tuta absoluta* and felt its impact on their tomato crop. There was a higher percentage of respondents in Kenya who had encountered the problem of *Tuta absoluta* the previous season (47.5%), or several seasons ago (52.3%) (Table 3). Similarly, in Zambia, 59.4% of the respondents had seen the problem the previous season, and 40.4% has encountered the problem in the previous seasons. In general, the data suggest that farmers in both countries have lived with *Tuta absoluta* for a number of years, which is not surprising as this pest was first reported to have invaded Kenya in June 2014, and Zambia in May 2016.

Table 3: Time when *Tuta absoluta* was first encountered in the field

Cropping season seen *Tuta absoluta*	Kenya % (n=398)	Zambia % (n=426)
This (current) cropping season	0.0	0.2
The previous cropping season	47.5	59.4
A few cropping seasons ago	52.3	40.4

2.3 Infestation levels of *Tuta absoluta* on tomato

Farmers' responses on the proportion of tomato infested by *Tuta absoluta* varied between Kenya and Zambia. Whereas in Kenya most farmers reported that a minor part of the crop (53%) or about half of the crop (20%) was affected by *Tuta absoluta*, in Zambia the infestation levels were higher, with the majority of farmers (close to 50%) reporting a major part or entire area of their tomato crop being infested, and 27% of farmers reporting about half of their crop being infested (Table 4). This suggests that *Tuta absoluta* is more of a problem in Zambia than in Kenya.

Table 4: Proportion of tomato-cultivated land infested by *Tuta absoluta*

Proportion of tomato crop	Kenya % (n=397)	Zambia % (n= 425)
A very minor part (<10%)	17	5
A minor part (10% to 40%)	53	19
About a half (41% to 60%)	20	27
A major part (61% to 90%)	9	32
The entire area (>90%)	2	17

Pest counts on the traps, for an average of the 1-hour to 1.5-hour household interview duration, showed, in general, low pest abundance in most of the studied locations. However, in some locations at least 28.5% of the traps in Kenya, compared to 27.7% in Zambia, captured 1–50 adults (Table 5). Approximately 1% of traps in Kenya collected more than 200 adults, with the highest capture being 225 adults, at Kajiado County. Although this data may not necessarily reflect the true *Tuta absoluta* infestation given the short time it was collected and the many factors that influence pest abundance and damage, it does provide a snapshot on the severity of an attack by this pest under certain conditions.

Table 5: Trap catches of *Tuta absoluta* over a 1-hour to 1.5-hour period

Number of adult moths	Kenya % (n=400)	Zambia % (n= 394)
0	67.8	72.1
1–50	28.5	27.7
51–100	2.5	0.3
101–150	0.5	0.0
151–200	0.3	0.0
201–250	0.5	0.0

There was higher fruit and leaf damage in Zambia compared to Kenya (Table 6). Leaf damage was the most predominant symptom of *Tuta absoluta*, with 12.8% of plants sampled in Kenya exhibiting this damage, and 34.1% of the plants in Zambia showing damage to the leaves. The highest fruit damage was observed in Zambia (18.5%).

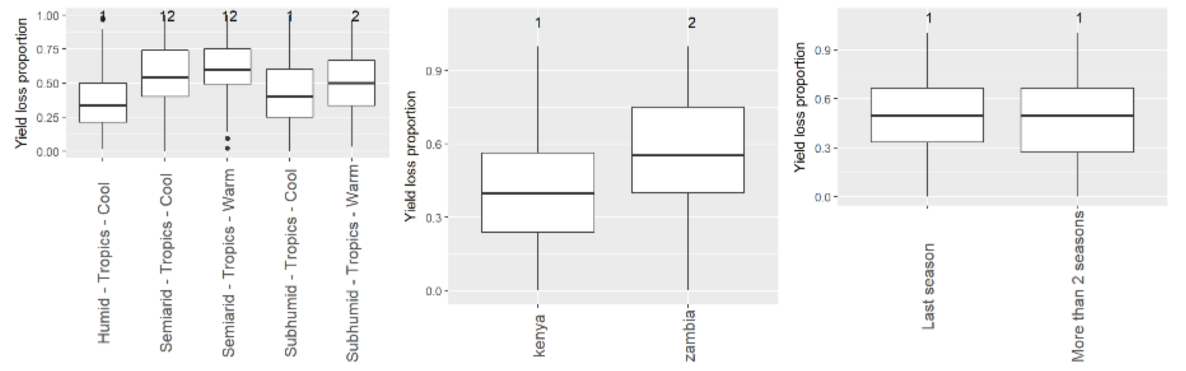
Table 6: Level of *Tuta absoluta* damage scored by enumerators

Symptoms	Kenya %	Zambia %
Leaf damage	12.8	34.1
Fruit damage	4.3	18.5
Fruit and leaf damage	3.4	16.0

2.4 Production loss estimation due to *Tuta absoluta* attack

In order to determine the production loss, farmers were asked to provide an estimate of their current production (farmer recall), as well as the potential production had they not had *Tuta absoluta* (farmer prediction) for the previous season (2017). The production loss (%) was then estimated as the relative change between both production values per year (see methods in Abrahams *et al*., 2017). From our study, 99% of farmers were affected by *Tuta absoluta*, hence the recall-prediction method was the most feasible. Using the recall-prediction method, differences in estimated yield loss were compared across agro-ecological zones (AEZs), countries and time since *Tuta absoluta* was first seen (last season or a few crop seasons ago). Comparisons were made in a full regression model pooling data from Kenya and Zambia. Including all factors in a single model we were able to compare yield loss across AEZs, taking into account country and season differences (Figure 8).

Figure 8: Boxplot comparison of yield loss proportion in Kenya and Zambia



Note: *Across AEZs (left), countries (centre) and time since Tuta absoluta was first seen at farm level (right). For each level, the boxes indicate the lower quartile (bottom horizontal line), median (central horizontal line) and upper quartile (top horizontal line). The same numbers above levels indicate that yield loss values are significantly similar*

On average, farmers reported a higher production loss due to *Tuta absoluta* in Zambia (mean 57%, lower quartile 40%, upper quartile 75%) than in Kenya (mean 41%, lower quartile 24%, upper quartile 56%). Production loss estimated by farmers across AEZs did not have large differences. Production loss was only significantly higher in the sub-humid tropics – warm AEZs compared to the other humid and sub-humid areas (Figure 8). Farmers who indicated recent arrival of *Tuta absoluta* (last season) reported similar yield loss to farmers with earlier *Tuta absoluta* arrival. When the data from both countries were pooled, the average production loss reported was 49% (lower 40%, upper 66%). However, it should also be borne in mind that these losses are estimated from farmer recall and prediction, and there could be over-estimation in some instances as it is likely that with increased pesticide use, the problem is being managed (see also Section 1.4 on yield losses identified in the literature review).

2.5 Estimates of production and economic loss due to *Tuta absoluta* based on farmer recall and prediction

The tomato production (five-year average pre-*Tuta absoluta*) and estimated lower and upper production and economic losses are given in Table 7. The loss values were estimated using the lower quartile of production loss as perceived by farmers in each country (see section above). The production loss was estimated at 114,000 tonnes for Kenya and 10,700 tonnes for Zambia. This translates to US$ 59.3 million and US$ 8.7 million in economic losses for Kenya and Zambia, respectively. We considered the lower quartile for estimation as it is highly probable that with the increased use of insecticides in both countries, the production losses might be over-estimated. Generally, a major shortcoming of the farmer recall and prediction data collection method is that estimates are not necessarily always highly accurate. We recommend that more specific field research studies to determine yield losses be conducted under no control and with currently used farmer practices. Further studies should also extrapolate economic impacts considering that with the frequent use of pesticides, production loss might not be reduced significantly, but the health impacts may likely increase, resulting in less time spent on economic activities.

In order to understand the potential losses across major tomato-producing regions in sub-Saharan Africa, the perceived losses of tomato to *Tuta absoluta* reported by farmers in

Kenya and Zambia were also extrapolated across agro-ecologically similar countries (>80% overlap) to obtain an estimate of potential losses and their associated economic value in a scenario where *Tuta absoluta* becomes established across all tomato production areas in these countries. Losses are indicative of those experienced by farmers after at least one season's experience of *Tuta absoluta*, i.e. farmers are likely to be expectant of the pest and to use measures such as insecticide application to limit losses, rather than suffer the frequently reported losses of up to 100% experienced on first arrival of *Tuta absoluta* in a new country, where farmer preparation is generally minimal and appropriate management approaches for *Tuta absoluta* are limited or delayed. The total estimated national production and revenue losses for Kenya, Zambia and 10 additional major tomato-producing countries in Africa that share common international AEZs with Zambia and Kenya are also summarized in Table 7. Major tomato producers in sub-Saharan Africa, such as South Africa, Cameroon and Ghana, were not included in the estimation as they share limited AEZ overlap with the two study countries, Kenya and Zambia. In addition, North African countries were excluded from the extrapolation due to differences in tomato production systems compared with smallholders in sub-Saharan Africa. Tomato production losses to *Tuta absoluta* in these countries would be additional to those reported here, and could be very significant given the scale of production in each. Losses were related to total expected tomato production and value in each country, based on average yields and crop values pre-*Tuta absoluta*, and focused only on production in AEZs shared with Zambia and Kenya. The lowest loss limits (derived from the combined average of Kenya and Zambia dataset) were used for each of the countries.

Table 7: Expected tomato production and estimated production and economic losses (lower quartile) based on extrapolation of perceived farmer losses from Kenya and Zambia

Country	National production (five-year average 2009 to 2013) (1000 tonnes)	National production value (million US$)	Production loss [lower] (1000 tonnes)	Production loss [lower] (million US$)
Kenya	480.3	249.0	114.3	59.3
Zambia	26.7	21.7	10.7	8.7
Nigeria	1,805.3	1,699.2	526.7	495.7
Tanzania	342.7	109.5	101.5	32.4
Mozambique	217.0	203.4	63.6	59.6
Benin	191.7	139.7	57.3	41.7
Senegal	163.0	42.8	47.5	12.5
Rwanda	123.5	68.4	37.1	20.5
Niger	118.2	126.8	35.5	38.0
Mali	75.0	39.0	22.5	11.7
Ethiopia	54.5	12.5	16.2	3.7
Malawi	40.2	25.7	12.1	7.7
Total	**3,638.1**	**2,737.7**	**1,045.0**	**791.5**

The estimates indicate that for these countries taken together, the potential impact of *Tuta absoluta* on sub-Saharan Africa tomato production is at least 1.05 million tonnes lost annually, out of the total expected production of 3.64 million tonnes, with economic losses of at least US$ 791.5 million annually, of the total expected value of US$ 2,737 million. As mentioned earlier, due to the possibility of over-estimation, these values should be validated with actual experimental data. We therefore also defined a fixed yield loss value and extrapolated it to the production value of tomato for each country, and the estimates of economic losses from the survey values match with a yield loss of between 25% and 30% (Table 8).

Table 8: Published statistics on tomato production and estimated economic losses based on extrapolation of a defined yield loss value

Country	Production value (million)	5% loss	10% loss	15% loss	20% loss	25% loss	30% loss	35% loss	40% loss
Kenya	249.0	12.5	24.9	37.4	49.8	62.3	74.7	87.2	99.6
Zambia	21.7	1.1	2.2	3.3	4.3	5.4	6.5	7.6	8.7
Nigeria	1,699.2	85.0	169.9	254.9	339.8	424.8	509.8	594.7	679.7
Tanzania	109.5	5.5	11.0	16.4	21.9	27.4	32.9	38.3	43.8
Mozambique	203.4	10.2	20.3	30.5	40.7	50.9	61.0	71.2	81.4
Benin	139.7	7.0	14.0	21.0	27.9	34.9	41.9	48.9	55.9
Senegal	42.8	2.1	4.3	6.4	8.6	10.7	12.8	15.0	17.1
Rwanda	68.4	3.4	6.8	10.3	13.7	17.1	20.5	23.9	27.4
Niger	126.8	6.3	12.7	19.0	25.4	31.7	38.0	44.4	50.7
Mali	39.0	2.0	3.9	5.9	7.8	9.8	11.7	13.7	15.6
Ethiopia	12.5	0.6	1.3	1.9	2.5	3.1	3.8	4.4	5.0
Malawi	25.7	1.3	2.6	3.9	5.1	6.4	7.7	9.0	10.3
Totals	**2,737.7**	**136.9**	**273.8**	**410.7**	**547.5**	**684.4**	**821.3**	**958.2**	**1,095.1**

2.6 Methods used by farmers to manage *Tuta absoluta*

According to the household survey, five different methods were deployed to control *Tuta absoluta* in Kenya, and two methods in Zambia (Table 9). Use of pesticides was the predominant method deployed by farmers to control the pest in both countries, with 96.5% of farmers in Kenya using this method, and 97.6% of farmers in Zambia. Less than 1% of farmers in Kenya used pheromone traps, which is a lower-risk method of pest control. Several companies in Kenya, such as Kenya Biologics Ltd, Koppert Biological Systems, Dudutech, and Ltd Real IPM (Biobest Group), are promoting the wider use of pheromones for mass trapping of this pest, which might explain their use in the country, although the levels remain very low. About 1.5% of farmers in Kenya, and 1.4% of farmers in Zambia, did not practise any method for managing *Tuta absoluta*.

Table 9: Most common *Tuta absoluta* control practices used

Control practice	Kenya (n=396)	Zambia (n=417)
Chemical pesticide	96.5%	97.6%
Pheromone traps	0.8%	0.0%
Destroying infected plants	0.8%	1.0%
Staking	0.3%	0.0%
Organic pesticide	0.3%	0.0%
No control practice	1.5%	1.4%

2.7 Effectiveness of different control methods against *Tuta absoluta*

Since the majority of farmers in both countries used pesticides, we sought to understand if this method is effective. Surprisingly, only 27.2% and 17.2% of farmers in Kenya and Zambia, respectively, reported the method to be very successful (Table 10). The majority in both countries (65.5% in Kenya and 59.7% in Zambia) reported the method to be only fairly successful. Furthermore, 7.3% of farmers in Kenya and up to 23.1% of farmers in Zambia reported that pesticides were not an effective method to control *Tuta absoluta*. This is unusual for a method that is very widely used by nearly all farmers.

Table 10: Most common *Tuta absoluta* control practices used and their effectiveness

Control practice	N	Percentage of households		
		Very successful	Fairly successful	Not successful
		Kenya		
Chemical pesticide	382	27.2	65.5	7.3
Pheromone traps	3	66.7	33.3	0.0
Destroying infected plants	3	0.0	100.0	0.0
Others	3	33.3	66.7	0.0
		Zambia		
Chemical pesticide	407	17.2	59.7	23.1
Destroying infested plants	4	0.0	75.0	25.0

Others = Staking, organic pesticide, crushing larvae

2.8 Analysis of pesticides used for *Tuta absoluta* control

During the survey, farmers provided trade names for the products (30 in Kenya, 39 in Zambia) they were using, which we converted to active ingredients.

2.8.1 Pesticide use in Kenya

Farmers in Kenya used a wide range of insecticides for the management of *Tuta absoluta* (Table 11). Products with the active ingredient Chlorantraniliprole (51.8%), Flubendiamide (47.6%) and Alpha-cypermethrin (30.1%) were the most widely used.

Table 11: Top pesticides used in Kenya (n=382)

Active ingredient and pesticide class	No. of farmers	% of farmers
Chlorantraniliprole (Class n)	198	51.8
Flubendiamide (Class n)	182	47.6
Alpha- cypermethrin (Class II)	115	30.1
Lambda-cyhalothrin (Class II)	72	18.8
Emamectin benzoate (Class n)	45	11.8
Imidacloprid (Class II)-Neonicotinoid	43	11.3
Chlorpyrifos (Class II)	23	6.0
Acephate (Class II)	19	5.0
Abamectin (Class n)	16	4.2

Key: Ia = extremely hazardous; Ib = highly hazardous; II = moderately hazardous; III = slightly hazardous; U = unlikely to present acute hazard in normal use; n – not listed [list published in 2009 (WHO, 2010)

2.8.2 Pesticide use in Zambia

In Zambia, the top products used for *Tuta absoluta* control were those containing the active ingredients Emamectin benzoate (33.2%), Flubendiamide (24.8%) and Abamectin (23.6%) (Table 12). About 6.4% of farmers used Monocrotophos, a WHO Class 1b pesticide. The regulatory authority has not provided a list of all registered pesticides in Zambia to determine the registration status of the products farmers reported that they had used.

Table 12: Top pesticides used in Zambia (n=407)

Active ingredient and pesticide class	No. of farmers	% of farmers
Emamectin benzoate (Class n)	135	33.2
Flubendiamide (Class n)	101	24.8
Abamectin (Class n)	96	23.6
Lambda-cyhalothrin (Class II)	67	16.5
Cypermethrin (Class II)	29	7.1
Monocrotophos (Class Ib)	26	6.4
Profenofos (Class II)	15	3.7
Malathion (Class III)	10	2.5
Chlorpyrifos (Class II)	12	3.0

Key: Ia = extremely hazardous; Ib = highly hazardous; II = moderately hazardous;
III = slightly hazardous; U = unlikely to present acute hazard in normal use;
n – not listed [list published in 2009 (WHO, 2010)

In Kenya, the majority of farmers applied one to five insecticide sprays (73.1%) or six to 10 sprays (19.9%) per season of three months (Table 13). About 1.0% of farmers applied 21 to 25 sprays, and in 0.8% of the cases farmers applied more than 30 sprays. In Zambia, the majority of farmers applied between six to 10 insecticide applications (33.9%) per season, although a sizeable proportion (29.2%) only applied one to five sprays. Considering farmers who applied 16–30 insecticide applications in Zambia, nearly 27.4% of farmers fell into this category (Table 13). Clearly more pesticides are being used on tomato in Zambia than in Kenya. This level of pesticide use against *Tuta absoluta* is comparable to the Mediterranean Basin, where in the first years after detection it led to a substantial increase in insecticide applications. At that time, up to 15 insecticide applications specifically targeting *Tuta absoluta* were added to existing IPM schemes (Desneux *et al*., 2011). In Brazil, more than 30 applications have been reported (Campos *et al*., 2015). However, these comparisons must be interpreted with caution as the toxicity levels of the pesticides used in Zambia, for instance, is higher than what might be acceptable in Spain.

Table 13: Number of pesticide sprays against *Tuta absoluta*

No. of pesticide sprays	Kenya % (n=382)	Zambia % (n=407)
1– 5	73.1	29.2
6–10	19.9	33.9
11–15	3.2	8.7
16–20	1.9	17.7
21–25	1.0	8.6
26–30	0.3	1.1
31–35	0.5	0.0
36–40	0.3	0.3

2.8.3 Analysis of highly toxic pesticides used for *Tuta absoluta* control

This study identified six active ingredients in Kenya and a similar number in Zambia that are considered to be highly toxic (WHO Class 1b), some of which are banned or restricted by international agreements. For instance, 7.9% of farmers in Kenya used Beta-cyfluthrin and 6.4% in Zambia used Monocrotophos (Table 14). This is a major concern, especially recognizing that several sprays are being applied. In countries where such products are still used, application is usually recommended only on non-food products. It was not clear if farmers were buying such products for their registered use, and diverting it for tomato, but we assume that using such products for *Tuta absoluta* control in tomato is illegal in both countries. For instance, the pest control products registered for use in the Kenya catalogue (Pest Control Products Board, 2017) provides the following use for Beta-cyfluthrin: "An agricultural insecticide for the control of thrips, aphids, whitefly nymph and caterpillars on roses; and aphids in cotton. Not for foliar use on fruits and vegetables." Clearly, farmers are diverting the use of this product to tomato illegally. The side effects reported by farmers using such products were largely in line with the effects indicated on the pesticide label. The use of such products on cultivated foods, such as tomato, should be discouraged, even if they are registered for other specific uses.

Table 14: List of highly toxic pesticides used against *Tuta absoluta*

Active ingredient	WHO classification	Country	No. of farmers	% of farmers
Beta-cyfluthrin	1b	Kenya	44	7.9
Monocrotophos	1b	Zambia	26	6.4
Metamidophos	1b	Zambia	7	1.7
Methomyl	1b	Zambia	4	1.0
Dichlorvos	1b	Zambia	1	0.3

In both countries, a few farmers use low-risk products for managing *Tuta absoluta* (Table 15). One reason for the low uptake of low-risk options is the cost: the data show that most of the higher-risk products are cheaper. Pheromones, for instance, were reported by two farmers to be very successful in controlling this pest, but the number of farmers using this method remains few. The study did not find any companies that sell pheromones in Zambia, however a number of firms in Kenya stock these products, including imports by foreign-based companies. It should be emphasized that mass trapping through pheromones as a single method may not be a reliable control method for managing *Tuta absoluta*, but pheromones are an integral component of IPM for monitoring and mass trapping.

Table 15: Low-risk pest control products for *Tuta absoluta* control

Pest control product	No. of farmers	% of farmers
		Kenya (n=382)
Nimbecidine	2	0.5
		Zambia (n=407)
GS-omega/kappa-Hxtx-Hv1a	6	1.5
Nimbecidine	6	1.5
Pheromone	3	0.7

2.9 Cost of applying pesticides

2.9.1 Kenya

According to the household survey, the average amount spent on pesticides per household amounted to KES 4,864 (US$ 47.2), which is approximately US$ 33.7/ha. However, when we consider the top three pesticides used, farmers spent on average KES 5,022 (US$ 48.7) on Chlorantraniliprole, KES 9,250 (US$ 89.7) on Flubendiamide and KES 2,575 (US$ 25.0) on Alpha-cyperpermethrin. Therefore, based on the top three products alone, farmers spent on average KES 5616 (US$ 54.4), amounting to US$ 39.0/ha every season. When we consider cost/spray, the average farmer in Kenya spent KES 1250 (US$ 12.3) per season on their tomato crop.

2.9.2 Zambia

The average amount spent on pesticides per household amounted to ZMW 504 (US$ 42.1), which is approximately US$ 9.4/ha, which is more than threefold cheaper than Kenya. When we consider the top three pesticides used, farmers spent on average ZMW 384 (US$ 32.0) on Emamectin benzoate, ZMW 451 (US$ 37.7) on Flubendiamide and ZMW 362 (US$ 30.2) on Abamectin. Therefore, based on the top three products alone, farmers spent on average ZMW 399 (US$ 33.3), amounting to US$ 7.4/ha every season. When we consider cost/spray, the average farmer in Zambia spent ZMW 43 (US$ 4.2) per season on their tomato crop.

2.10 Pesticide safety

A key issue around pesticide use for managing *Tuta absoluta* is the high number of sprays, which could pose a risk to human health. Pesticides in tomato production are frequently applied without appropriate safety precautions being taken, and in the current study the majority of farmers in both countries (>60%) used PPE. However, 34.8% of farmers in Kenya and 38.3% in Zambia did not use any PPE (Table 16).

Table 16: Proportion of farmers who wear at least one piece of protective gear

Country	Yes (%)	No (%)
Kenya (n=382)	65.2	34.8
Zambia (n=407)	61.7	38.3

For the farmers who used PPE, more than 50% in both countries used gumboots, approximately 40% used overalls, and between 27% and 33% used face masks (Table 17). In Kenya, 17.8% used gloves, while at least 29.3% in Zambia also used gloves.

Table 17: Type of protective gear worn by farmers during spraying

Protective gear	Kenya % (n=382)	Zambia % (n=407)
Gum boots	56.4	53.0
Overall	40.0	39.9
Mask	32.8	26.8
Gloves	17.8	29.3
Cap	7.3	8.9
Goggles	4.1	10.9

We explored further the side effects from using pesticides, and found that around half of farmers in both countries reported health effects from using pesticides. These values represent the percentage of farmers who reported that they experienced these health symptoms during or after the spraying of pesticides to control *Tuta absoluta*. Skin itching was among the most frequently reported side effect, with 30.6% of farmers in Kenya and 24.8% in Zambia reporting this symptom (Table 18). Nearly 31.5% of farmers in Zambia reported headaches as a side effect, while other side effects included stomach aches and dizziness.

Table 18: Pesticide-related health symptoms associated with *Tuta absoluta* control

Health symptoms	Kenya % (n=382)	Zambia % (n=407)
Skin itching	30.6	24.8
Dizziness	17.0	13.8
Headache	10.7	31.5
Stomach ache	2.9	9.6
Others*	4.2	27.8

**Others included sneezing, coughing, eye irritation, vomiting and nosebleeds*

2.11 Potential impacts of *Tuta absoluta* on trade

Tuta absoluta is recommended for regulation as a quarantine pest in the EU, and exporting countries may be required to apply mandatory phytosanitary procedures, which results in extra costs to exporters and the national plant protection organization. However, there do not seem to have been major impacts of *Tuta absoluta* on trade. The number of interceptions of commodities with *Tuta absoluta* in the EU remains low, and there do not seem to be significant trade barriers related to this pest, although it ranks high as a quarantine pest. Within a five-year period (2013–2017) there was only one interception in the EU of *Tuta absoluta*, on *S. lycopercicum* originating from Morocco in 2015. In 2018, the interceptions of commodities with *Tuta absoluta* increased. For instance, from Africa alone, there were 12 interceptions on *S. lycopercicum*, and one on wood packaging material from Tunisia. Other countries with interceptions include Albania (1) and Lebanon (1). Nevertheless, this level of interceptions, over a long period of time, suggests that countries are managing *Tuta absoluta* well and taking all the necessary precautions.

In conclusion, our data suggest that *Tuta absoluta* is a serious threat to tomato production where it occurs. What is most worrying is the number of pesticide sprays and the highly hazardous products that are being deployed, some banned internationally, which pose serious health risks to farmers or the individuals doing the spraying. To minimize human health impacts such products should not be registered for *Tuta absoluta*, even where they are registered for other uses. Pest control products are also sprayed on ripening tomatoes, and because farmers do not observe pre-harvest intervals, a lot of these toxic substances are likely to enter into the human food chain, posing long-term health risks, which is clearly a threat for the consumer. For instance, in Ghana, an old study analysing pesticide residue levels on tomato showed that chlorpyrifos, a pesticide used by farmers on tomato in the present study on *Tuta absoluta*, had the greatest residue level of 10.76 mg/kg (Essumang *et al*., 2008). A human health risk assessment from the same study showed high cancer risk for adults and children due to the presence of chlorpyrifos. There is a need for a systematic study to assess the current situation in African countries where high pesticide use against this pest is prevalent.

3. Management of *Tuta absoluta*

Like many other pests, *Tuta absoluta* is a major threat to the production of tomato (and other cultivable Solanaceae members). As such, detection, correct identification (of pest and damage) and the threshold levels are key in the control of this pest. Several approaches have been used for monitoring and controlling *Tuta absoluta*, both in the native and exotic ranges of the pest. Biondi *et al*. (2018), Giorgini *et al*. (2018) and Mansour *et al* (2018) provide substantial details and references on these control methods, and these publications may be referred to for additional information. Therefore, we only provide a short review of each method below, and we also provide in Table 19 a summary of the key options that might be suitable for Africa.

3.1 Pheromone lures

Sex pheromones are chemicals secreted by an organism to attract individuals of the opposite sex of the same species for mating (Megido *et al*., 2013). Mating in *Tuta absoluta* occurs as a result of attraction of the male towards the pheromones released by the females. Sex pheromones have been widely used in the detection and monitoring of insect pests, including *Tuta absoluta* (Witzgall, *et al*., 2010). Control of this pest can also be achieved through use of pheromones, mainly through mass trapping (attraction of one or both sexes to a lure, in combination with a large-capacity trap), or the attract-and-kill option (an additional insecticide-impregnated target). The benefit with the use of pheromones is that there is no pre-harvest interval required if this is the only method used.

3.1.1 Monitoring of *Tuta absoluta* using pheromones

Method: Pheromone traps can give early warning of infestation and will accurately capture the *Tuta absoluta* densities in low-population to medium-level infestation. Only males are captured in pheromone traps, when they are looking for females to mate with, and when pheromones are used for monitoring the captures show the presence of the pest and when its seasonal flight period starts. This is important in determining the threshold levels either for the timing of control procedures, or for making a decision whether or not remedial action is to be taken (Witzgall *et al*., 2010).

Effectiveness: In heavy infestation, pheromone traps tend to give high levels of capture, which makes data collection difficult. Other products are specifically designed to give a lower capture rate to make data collection in heavily infested fields manageable. An important factor when using pheromones for monitoring is the standardization of the traps (the attractant, dispenser, trap design, and trap location). Also, the attractant and dispenser material must be subject to strict quality control, since release rates and chemical impurities, even in trace amounts, will strongly affect the attractiveness of a lure (Arn *et al*., 1997). Caparros Megido *et al*. (2013) have shown that the number of male captures in a pheromone trap is not necessarily indicative of crop damage and cannot be associated with an economic threshold. However, it will aid the farmer to detect the beginning of the pest attack and the population dynamics, which is crucial for initiating control measures.

Cost: The main suppliers of pheromone products in Kenya are Dudutech and Kenya Biologics Ltd, while some products are also imported from Russell IPM in the UK. We did not find any suppliers of pheromone products for *Tuta absoluta* in Zambia. A smallholder grower will require one set; this includes a paper sticker for catching the moths (US$ 0.5), pheromone (US$ 3), and a trap at US$ 3 (total: US$ 6.5).

3.1.2 Mass trapping

Method: This control method refers to a technique that involves placing a higher number of pheromone traps (45–50 traps per hectare) in the crop field in various strategic positions to remove a sufficiently high proportion of male insects from the pest population. This reduces mating incidences and, as such, the number of viable eggs. With less or no hatching of *Tuta absoluta* eggs*,* the population is significantly reduced, and this can eventually cause the population to crash. The trap may be a simple bucket trap, containing water at the bottom that drowns the moths that enter the device. This method is useful in greenhouses, particularly if insect exclusion nets and tight doors are used.

Effectiveness: This can be an effective method, reducing a significant population of the pest. Some products have high capture rates, which makes them ideal in mass capture of the *Tuta absoluta*, especially in protected cultivation, with some potential for use in open field cultivation. Mass trapping is often used in combination with other control measures to achieve at low cost and in an environmentally safe way the acceptable control of *Tuta absoluta*. Light traps may also be used for mass trapping of *Tuta absoluta*, especially in low–medium infestation levels. However, these have only been used so far on an experimental basis and are not likely to be applicable in open field smallholder production. Russell IPM and Koppert Biological Systems have also developed an innovative *Tuta absoluta* trap where light and pheromones are combined to maximize trap catch. The solar powered light trap is able to capture both the female *Tuta absoluta* moths as well as the male, providing an increased level of control when compared with sex-specific monitoring devices. The operating principle of this method is based on the synergy of sex pheromone and a particular light frequency to which *Tuta absoluta* is most attracted. The method utilizes a specific wavelength of light in combination with sex pheromones to lure the moths into the water-based trap. The plastic base is simply filled with water and a thin layer of oil to trap and contain the pests without the use of toxic chemicals or pesticides. The device switches on during the three to four hours before sunrise, as extensive testing has shown that this period results in the highest number of moth catches. Therefore, the trap light is controlled through a regulator that activates the light source in the last quarter of the night to maximize the trap efficacy.

Cost: In Kenya, one company is selling the paper sticker for catching the moths at US$ 0.5, pheromones at US$ 3, and the device that holds the whole system at US$ 3 (total: US$ 6.5). Assuming 1 ha will require 40 traps for the open field, the cost to the farmer would reach US$ 260. While modern pheromones are designed to last the cropping cycle, the paper sticker would need to be replaced nearly weekly, which would drive the cost far above what a smallholder farmer could afford for this method.

3.1.3 Mating disruption

Method: Although still under development, mating disruption offers next generation tools for *Tuta absoluta* control, and can reduce the number of insecticide sprays that might be needed (Cocco *et al*., 2012). Based on synthetic sex pheromone, this method causes disorientation and communication disruption between the sexes. Thus, male *Tuta absoluta* moths cannot find females to mate with, which delays, reduces, or prevents fertilization of females. The method reportedly confers complete population control with no visible crop damage during the first four months of the crop; however, it is ineffective in preventing economic losses when applied in the open field or unscreened greenhouses (Vacas *et al*., 2011).

Effectiveness: Trials on containment level revealed that the flight of *Tuta absoluta* was satisfactorily disrupted with an initial pheromone dose of 30 g ha(-1), and levels of damage did not significantly differ from those in reference plots with insecticide treatments (Vacas *et al*., 2011). Further, release studies showed that control of damage and flight disruption occurred when releasing at least 85 mg pheromone/ha/day. Cocco *et al*. (2012) showed that mating disruption pheromone dispensers applied at the density of 1000/ha significantly reduced the percentage of damaged fruits by 62–89%.

Cost: Mating disruption could be most ideal in greenhouse tomato production, as it can saturate the atmosphere in a short time. However, the Isonet-T dispensers are still being tested. It is thought that, theoretically, this method could lead to female moths that are capable of producing eggs without mating.

3.2 Chemical control

Method: For a long time, chemical control (use of synthetic pesticides in pest management) has been the go-to option in the management of *Tuta absoluta* (Guedes and Picanço, 2012). However, initial reliance on organophosphates, pyrethroids, Cartap and Abamectin has shifted to insect growth regulators and, more recently, to novel insecticides. Data from Brazil showed that tomato farmers carried out up to 36 insecticide applications to control *Tuta absoluta* within one cropping season (Campos *et al*., 2015). In Spain, up to 15 insecticide applications specifically targeting *Tuta absoluta* were added to existing IPM schemes after the pest was first detected (Desneux *et al*., 2011). However, these comparisons must be interpreted with caution as the toxicity levels of the pesticides used in Zambia, for instance, is higher than what might be acceptable in Spain. In Europe, there has been extensive use of insecticides since the arrival of *Tuta absoluta* (Desneux *et al*., 2010). This has potential negative effects not only on the environment but also the beneficial organisms (Desneux *et al*., 2007). Also, chemical residues in fruits after application are a concern, especially with extensive use of chemicals.

Effectiveness: Chemical control, however, is sometimes not very effective in the management of *Tuta absoluta*. The endophytic behaviour of the larvae (being found in the mesophyll of leaves) makes it hard for the chemical to reach the pest (Retta and Berhe, 2015). Also, the pest has the ability to rapidly develop resistance, and resistant populations have already been recorded in Italy, Greece and Israel (Roditakis *et al* 2018). *Tuta absoluta* has been reported to be resistant to a number of insecticides (Herbert *et al*., 2005; Lietti *et al*., 2005; Silva *et al*., 2011; Roditakis *et al*., 2018). *Tuta absoluta* has been reported to develop resistance to cartap, abamectin and pyrethroids (Siqueira *et al*., 2001; Siqueira *et al*., 2005), organophosphates, spinosad, Emamectin benzoate and abamectin (Guedes and Picanço, 2012), chloride channel activators, benzoylureas (Campos *et al*., 2014) and diamides (Khalid, 2011; Roditakis *et al*., 2015; Silva *et al*., 2016). There are no published data on insecticide resistance of *Tuta absoluta*, although we can predict that the currently observed indiscriminate use of pesticides could lead to resistant pest populations. As a rule, in chemical application, it is prudent to rotate different active ingredients and not to mix them at once so as to avoid build-up of resistance against the pesticides. The suggested active ingredients for rotation in the management of *Tuta absoluta* include: imidacloprid, indoxacarb, spinosad, deltamethrine (against adult moths) and rynaxypyr.

Cost: Small packets/bottles tend to be more expensive than larger ones, which makes the effective cost higher for small-scale farmers. Economically, the use of synthetic chemicals for the control of *Tuta absoluta* is likely to reduce the profit margins of the farmer due to the number of sprays that have to be carried out. The less toxic products are usually expensive and are likely to be out of reach of small-scale farmers, who are the majority of producers in Africa. Very often, the cheaper products are less costly and more readily available. Detailed analysis on the cost of pesticides is presented in section 2.9.

Action thresholds for chemical control

Two action thresholds exist in the management of pests: the economic threshold level (ETL), defined as the density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury levels, and economic injury level (EIL), the lowest population density that will cause economic damage (Stern *et al*., 1959). These IPM concepts are used to promote more rational use of pesticides, to avoid pesticide resistance, reduce problems with pesticide residues on agricultural products, and reduce negative effects of pesticides on non-target organisms**.** Different pests have different action thresholds at which control/management should be taken.

An intervention is economically justifiable if the value of the crop loss it reduces is more than the cost of the intervention. Determining the action threshold is useful in determining when an intervention is required. A study on the ETL and EIL of *Tuta absoluta* on tomato under open field conditions (Shiberu and Getu, 2018) found a linear relationship between tomato yield and pest larvae per plant during the period 2015–2017. It also showed a significant linear relationship between larval infestation and marketable yield loss when the tomato fruit and leaf were infested with larvae. The EIL and ETL were 3.82 and 2.87 larvae per plant, respectively, in Ethiopia. However, calculating thresholds requires sufficient data on yield, crop value, and cost of treatment under different production environments. It would be useful to determine the EIL and ETL for both open field and green house tomato across several African countries.

3.3 Microbial pesticides

Method: These are pesticide formulations that consist of a microorganism (e.g. a bacterium, fungus, virus or protozoan) as the active ingredient. Different microbial pesticides have been tested and found effective against *Tuta absoluta* (Abd El-Ghany *et al*., 2016). *Bacillus thuringiensis* var. *kurstaki* (Btk), *Beauveria bassiana*, and *Heterorhabditis bacteriophora* (an entomopathogenic nematode) were found to be effective against the larvae of *Tuta absoluta* (Abd El-Ghany *et al*., 2016). Studies on the efficacy of Btk showed that it was able to infect all the larval instars of *Tuta absoluta* (Giustolin *et al*., 2001). Btk was also found to be compatible with other control strategies. Entomopathogenic fungus *Metarhizium anisopliae* and *Beauveria bassiana* were found to be effective for use in the control of *Tuta absoluta*.

Studies have shown their ability to infect all stages of the pest (Moussa *et al*., 2018), causing female mortality of 37.14% and 68% for *M. anisopliae* and *B bassiana*, respectively.

Effectiveness: Biopesticides often act more slowly than chemical pesticides, which can reduce their attractiveness to farmers who prefer to see dead insects right after an application, as evidence that the method is working. Since *Tuta absoluta* has multiple overlapping generations, multiple sprays/application are required to control the vulnerable stages. Microbial insecticides, because they have a living organism as the active ingredient, are affected by unfavourable conditions (Moussa *et al*., 2018) and this negatively affects their efficacy. Some of the abiotic factors that affect microbial insects include high relative humidity, temperature and/or oxygen. The shelf life of these insecticides also has a negative relationship with efficacy. Batta (2003), in a study involving *M. anisopliae*, showed that showed that after 4.6 months, the viability of the spores was reduced by 50%.

Cost: In Kenya, South Africa, Ethiopia and Ghana, a commercial isolate Met69 is registered for use against *Tuta absoluta*. It is produced in two formulations: a total fermented product and a pure spores-in-oil product (Real IPM). A 500ml pack of the spores-in-oil formulation costs about US$ 25 and with an application rate of 200ml/ha at every spray, this cost is likely to be steep for a smallholder farmer.

3.4 Botanicals

Method: These are plant extracts used in the management of pests and may be contact or systemic. Several plants extracts have been used to control *Tuta absoluta*. For instance, azadirachtin, an extract from neem (*Azadirachta indica*) seeds, is used as a contact insecticide against *Tuta absoluta*.

Effectiveness: In an experiment involving *Tuta absoluta* eggs and larvae the neem extract resulted in a 24.5% egg and 86.7 to 100% larval mortality of the pest at different concentrations (Kona *et al*., 2014). From the same study, petroleum ether extract obtained from Jatropha, achieved 18% to 25% egg and 87% to 100% larval death after being exposed for four days in different concentrations. It is worth noting that under this study, the plant extracts did not have any impact on the viability of the eggs as the remaining eggs hatched post-four days' exposure (Kona *et al*., 2014). Neem oil applied on the adaxial side of the leaves or directly on the larvae has also shown efficacy against *Tuta absoluta*. Further neem corticated seeds extracts reduced the percentage infestation of tomato fruits and yield loss under greenhouse conditions. Other plants (garlic, basil, thyme, castor bean, eucalyptus, chinaberry, geranium and onion) have also been found to exhibit insecticidal activity with different efficacies against *Tuta absoluta* larvae (Abd El-Ghany *et al*., 2016; Birhan, 2018). A challenge with extensive use of neem extract is the photosensitivity of azadirachtin, which breaks down or isomerizes under sunlight; thus, neem has a low residual effect under field conditions (Ahmed, 2007; Madaki, 2015). Also, there are numerous variabilities in efficacy, especially in homemade formulations, as a result of poor standardization and quality control. With the availability of neem and other plants, the main cost involved is labour, which in farm-level production can be provided by family members.

Cost: Neem-based products are the most widely available botanical and cost US$12–15 for 1 litre, and require repeat applications. The higher cost of botanicals makes it very unlikely that smallholder farmers will purchase such products, particularly if they feel that pesticide works better. Further, many stockists do not stock such products, due to the low demand. In general, there is a lack of awareness about the benefits of the use of botanicals in IPM of insect crops.

3.5 Biological control

Method: Several studies have been carried out to assess which natural enemies are able to attack *Tuta absoluta* and potentially be used in a biological control approach. These are described in detail in Mansour *et al*. (2018) and include parasitoids and mirid predators. Implementing a biological control programme for *Tuta absoluta* would require applying the strategies as proposed by Mansour *et al*. (2018), namely: 1) mass-production for regular releases in fields affected by the pest (augmentative biological control); 2) adaptation of specific cultural practices (conservation biological control); and 3) exotic natural enemies from the pest native ranges could be introduced in Africa for permanent establishment (classical biological control). Currently, only augmentative biological control is being applied, and exclusively in Northern Africa, exploiting egg parasitoids and predatory bugs.

Effectiveness: The field parasitism of *Tuta absoluta* is generally low in Africa, although in the laboratory parasitism levels can reach 55%. Some successes have been reported with biological control in Tunisia, where a reduction of 87% and 78% in leaf damage was observed in greenhouse tomato after releasing a total of 25,000 adults of either parasitoid *Trichogramma cacoeciae* or *T.bourarachae*, respectively (Zouba *et al*., 2013). Additionally, the predatory mirid *Nesidiocoris tenuis* was shown to significantly reduce the density of *Tuta absoluta* eggs in Tunisian greenhouses (Ettaib *et al*., 2016). Importantly, this species can persist on tomato crops even when the density of *Tuta 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. *Tetranychu*s spp.) and (though to a lesser extent) thrips, therefore substantially contributing to the control of these pests (Giorgini *et al*., 2018). In the near future, classical biological control for this pest may also become a reality in Africa. The International Centre of Insect Physiology and Ecology imported the larval parasitoid *Dolichogenidea gelechiidivoris* into Kenya. Initial host suitability, acceptability and efficiency of this parasitoid in quarantine suggest that it prefers the early *Tuta absoluta* larval instars, with an average parasitism rate of over 60% (Mohamed, S., unpublished). While field evaluations have yet to be undertaken, the preliminary data do indicate that *D. gelichiidivoris* is likely to be a promising classical biological control candidate against *Tuta absoluta* that could potentially be released in much of Africa.

Cost: The estimated cost for a single inundative release of *N. tenuis* costs around US$ 68 for a 100 ml bottle containing 500 adults and nymphs. This probably makes it unattractive for open-field tomato smallholder growers, whose yield is much lower than that of large-scale commercial farms. It is likely that some macrobials could be produced in local rearing units, reducing the cost for the farmer. Classical biological control, on the other hand, is a one-off investment, and high benefit:cost ratios have been reported for a number of successful classical biological control programmes.

3.6 Resistant varieties

Method: Breeding programmes for tomato cultivars that are resistant to damage by *Tuta absoluta* have been active globally since the early 1990s, especially in Brazil, to explore host plant resistance as a strategy to manage the pest (Guedes and Picanço, 2012). Initial research focused on the role of leaf glandular trichomes in resistance. Studies by Ecole *et al*. (1999) showed that trichomes produce insecticidal compounds that are effective in the control of *Tuta absoluta* larvae*.* Recently, research into the role of allelochemicals and possible incorporation of the resistant genes (which were lost during domestication) from the wild types into commercial varieties is ongoing (De Oliveira *et al*., 2012). Allelochemicals (acyl sugars, zingiberene, and 2-tridecanone) and trichome density have been associated with conferring resistance to tomato against *Tuta absoluta* and other insect pests (Maluf *et al*., 2010; Resende *et al*., 2006). In studies to check the resistance of tomato strains to *Tuta absoluta,* the oviposition rate, plant damage severity, injuries to the leaflets and percentage of leaflets attacked were reduced by the presence of the allelochemicals (acyl sugars, zingiberene, and 2-tridecanone) (De Oliveira *et al*., 2012). Recent advances have looked at *Bt* tomato, which caused high mortality of *Tuta absoluta* larvae and a reduced formation of leaf mines (Selale *et al*., 2017).

Effectiveness: While pest-resistant tomato may have a role to play in the management of *Tuta absoluta*, on its own it is unlikely to be a sole solution. Further, even with extensive research in breeding programmes regarding resistant varieties, especially in South America, there is little information as to the actual success of such varieties, especially for commercial use (Zekeya *et al*., 2017). Much less information is available for the African continent and thus we do not anticipate any immediate prospects of this being a suitable approach in the short to medium term.

Cost: Bt crops are generally considered to be cost-effective, although depending on how many genes are stacked in the product, resistance could occur after some years. Traditional breeding is likely to cost the farmer less, however this appears to be a distant technology.

3.7 Netting technology

Method: Nets in *Tuta absoluta* management work by ensuring insect pest exclusion (influencing pest population dynamics). The advantage with using nets is that they reduce / eliminate chemical pesticide applications; produce quality and marketable fruits; contain / retain beneficial biocontrol agents; improve seedling germination, survival and transplant quality; and result in microclimate modifications (temperature, relative humidity, soil moisture, light), which is important for the tomato crop.

Effectiveness: Through netting technology, there is a 70% decrease in chemical sprays by farmers and a 35% to 70% increase in marketable yield of the tomato under nets.

Cost: A company in Tanzania, A to Z Textile Mills Ltd, produces the nets locally. A single net can be used for three to five years. However, the growers' gross margins and return on investment are not yet known, thus a project in Kenya is currently assessing the scalability of the technology.

3.8 Sterile insect technique (SIT)

Method: The SIT is an environmentally friendly control tactic that is based on the release of sterile insects to control individuals of the same species (Lachance 1985). Using SIT, it is possible to achieve a certain level of suppression of a *Tuta absoluta* wild population through the release of irradiated insects. However, this approach is less widely used for moths (Bloem and Carpenter, 2001).

Effectiveness: Lepidopteran species are more resistant to the sterilizing effects of radiation than insects of any other order (Lachance, 1985). However, Cagnotti *et al* (2016) showed that it was possible to achieve a certain level of suppression of a *Tuta absoluta* wild population through the release of irradiated insects.

Cost: SIT is only economically viable if large numbers of sterile insects can be produced at low lost. SIT also requires a special facility. Currently, the only known programme is in South Africa, where SIT is used for the control of false codling moth in fruit orchards. We believe that control of *Tuta absoluta* in Africa using SIT is not likely to be feasible for many years

3.9 Integrated Pest Management

Method: This is the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms (FAO and WHO, 2014). It involves a combination of all available control measures and strategies: cultural, physical, biological and judicious use of registered pesticides.

Effectiveness: Tuta absoluta has the ability to develop resistance to any control measure used singly (Mohamadi *et al*., 2017) and as such requires an integrated approach. It is this knowledge that has necessitated IPM research in many countries. Several success stories have been reported regarding IPM in the management of *Tuta absoluta*. Giorgini *et al*. (2018) reported that 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. In Egypt, an IPM component involving mass trapping *Tuta absoluta* males in red plastic basin traps at a density of eight traps / feddan, bi-weekly application of voliam flexi 40% WG (20% Thiamethoxam+ 20% chlorantaniliprole) and Dan top 50% WG (Clothianidin) in sequence during vegetative stage and weekly application of Dipel DF 6.4% WG (*Bacillus thuringiensis*) during fruiting stage was found to be more effective in reducing the damage (to between 1–5% damaged fruits) than the use of pheromones only or farmers' practices (Taha *et al*., 2013). It also emphasized the importance of sex pheromones in an IPM programme. This study also found that the spray/chemical application frequency in an IPM programme was lower (11 sprays) compared to the conventional farmers' practice (16 sprays).

Crop rotation with non-solanaceous crops is important as this will help in breaking the life-cycle of *Tuta absoluta*. This is a low-cost management strategy, but issues of long season and the need for food and income always limit adoption, especially for smallholder farmers. *Tuta absoluta* has a wide host range and removing wild relatives from the vicinity of tomato is important as this will eliminate alternative hosts, limiting the chances of the pest developing and moving to the next generation. Cultural practices like early scouting and/or monitoring are important in establishing early enough the presence of the pest, and for decision making. Destroying infested plants and plant parts helps limit the possibility of the pest at a particular life-stage from developing to the next and thus controlling the pest population. Also, inspection of the packaging equipment to ensure there are no eggs, larvae or pupae that might develop and spread is important. As such, fruits coming from foreign countries should be accompanied with a phytosanitary certificate. Proper fertilization provides the required nutrients to the plant and this gives the plant a competitive ability to tolerate pest damage. Studies show that *Tuta absoluta* takes longer to develop in fertilized soils (Mohamadi *et al*., 2017), i.e. developmental time, fecundity, and oviposition period. Irrigation not only provides an optimum environment for plant growth but also drowns the pest, which is useful in bringing down its population.

Cost: IPM offers good promise in terms of managing *Tuta absoluta*, particularly in the African context, given the production systems that exist. The costs involved in an IPM programme will largely depend on the individual combinations of control strategies. As such, they are variable. Also, labour considerations, especially where IPM involves multiple sprays, introduction of agents or even cultural practices, is an issue that needs to be looked into before deciding on the number of combinations. Overall, based on the effectiveness of the programme, IPM might offer the solution to the sustainable management of *Tuta absoluta*.

In conclusion, pesticides use remains the key strategy that farmers are using for managing *Tuta absoluta* in Africa, and indeed many regions invaded by the pest. The widespread use of pesticides is based on the premise that they offer better control than other management methods, and are usually easily accessible, largely due to aggressive marketing. However, the use of pesticides should not be considered the main substitute for the judicious management of this pest. The continuous use of some products is prone to result in insecticide-resistant populations, with farmers coping by using a cocktail of products, and in some cases highly hazardous products, in a bid to find what works for them. This is bound to result in some of the highest and most widespread pesticide risks, including both acute and chronic human health burdens. There is therefore a need to document the negative impacts of pesticides, such as the effects on the natural enemies of this pest and pollinators. Harder to quantify are the health and societal costs of pesticides for *Tuta absoluta* control, and hidden impacts such as economic cost of sickness to the country due to treatment of pesticide exposure, especially being cognizant of the number of sprays that are usually required. The criteria for pesticide recommendations for *Tuta absoluta* should include selecting those materials that may be used with minimal protective clothing (PPE), and which allow re-entry to the field one day or less after application. However, more effort is needed in promoting alternatives that are affordable, readily available, safe, effective, practical to use and combined with training on responsible use, especially pheromones and mass trapping, insect-proof nets, conservation and augmentation of natural enemies, and use of lower-risk products such as biorationals and biopesticides, all within a genuinely balanced IPM strategy. For instance, products such as biopesticides give slower control, and dead insects might not always be visible, and thus they may be perceived as less effective, thus there is a need for more training and information dissemination through mass extension campaigns, with credible information, by credible organizations that have the trust of the farmer, and with a long-term view for sustainable management of *Tuta absoluta*.

Summary and recommendations on control methods

Table 19 summarizes the main recommendations in relation to control of *Tuta absoluta* for open field tomato smallholder farmers, more commercial-oriented farmers using protected greenhouses, and government agencies. Recommendations are made on the basis of available evidence and technologies, and, where good evidence is not available, on the basis of reasonable assumptions. Several countries have developed pest management decision guides (PMDGs) for this pest that provide more information on prevention, monitoring, control and specific pesticide recommendations for the country concerned.

Table 19: Recommendations on control for African countries

Method	Availability in Africa	Recommendations for open field tomato smallholders	Recommendations for commercial farms	Recommendations for government
Monitoring: pheromone and sticky traps	Pheromone traps and lures commercially available in Africa, although not in all countries (e.g. TUAOptima, T.-CAPLong-life, TUA100N, Pherodis, Tutrack, T.san etc)	Use a pheromone trap to determine the threshold levels, either for the timing of control, or for making a decision whether or not remedial action is to be taken Insecticide treatments may be triggered when trap catches reach a threshold of three males per trap per day	Use three pheromone traps per 400 square metres in tomato greenhouse	Research on action thresholds for different situations (crop, growth stage)
Mass trapping: pheromones and water trap	Pheromones and traps are commercially available (see above). Little evidence that mass trapping is economically viable	Between 40 and 50 pheromone traps per ha in open field tomato recommended Little evidence that mass trapping is economically viable and effective in open field Useful when integrated with other IPM approaches	Recommended to use 20–25 pheromone traps per ha in tomato greenhouses	Consider subsidizing the cost of pheromones to make mass trapping more affordable in open field tomato production
Chemical control	Many are recommended' however, the lower-risk products are either not available or more expensive. Most products are foliar sprays	Use pesticides as a last resort, and only when economic thresholds are reached Use only pesticides recommended by the government for this crop Select lower-risk pesticides or selective insecticides if available/affordable, to protect mirid predators Rotate insecticides with different modes of action Follow all advice on safety, dilution, etc on the product label Buy only from registered pesticide dealers	Spray regime should be based on an action threshold that takes into consideration expected value of crop, expected loss if untreated, and cost of treatment Do not spray as a preventative measure Use pesticides recommended by the government, especially those with lower impact on natural enemies Rotate insecticides with different modes of action Use proper PPE when applying pesticides, and observe the re-	Monitor the health and environmental impacts of pesticides Prepare a technical guidance standard for pesticides: covering procurement, risk reduction and resistance management Monitor for pesticide resistance to most popular active ingredients Publish and make public the list of pesticides registered for *Tuta absoluta* Carry out rapid testing of new active ingredients of pesticides for their modes of action and low

Method	Availability in Africa	Recommendations for open field tomato smallholders	Recommendations for commercial farms	Recommendations for government
		Use proper PPE when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product	entry intervals and pre-harvest intervals of the product	environmental impact, including lethal and sub-lethal effects on field populations of beneficial arthropods, recognizing that farmers will continue to use such products in the foreseeable future
Biopesticides	Not commercially available in Africa. Strains of fungi (*Metarhizium, Beauveria*) and baculoviruses (NPVs) undergoing testing in several countries; commercial product still distant	Use registered biopesticide products instead of pesticides if available Rotate different Bt strains (that express different toxins) to prevent resistance	Use registered microbial biopesticides if recommended by government and effective against the larva of the pest Deploy innovative methods of spreading the bacteria or fungi within the adult population (e.g. autodissemination)	Accept supporting data from other countries for registration of biopesticides Provide temporary registration for products already registered in Europe and South America for this pest
Botanicals	Commercial neem products are available in some countries (e.g. Nimbecidine). Some essential oils tested in Africa (e.g. *Ocimum* sp)	Use neem products recommended by government instead of pesticides, whenever possible If no alternative, consider using homemade products made from neem, *Ocimum* sp. or other plants known to have pesticidal effect Farmers can prepare own neem solution by soaking 25–50 kg in 1 litre of water overnight, sieving and mixing in either 15 or 20 litres of water in a knapsack for spraying	Consider using neem products instead of chemicals Assess the efficacy of other products if available, and adopt for use	Accept supporting data from other countries for registration Work with international agencies to test locally manufactured and homemade botanical pesticides, particularly essential oils and produce formulations that maximize the toxic effect on *Tuta absoluta* and reduce side effects on beneficial arthropods
Biological control	Predatory mirids *Nesidiocoris tenuis* and *Macrolophus pygmaeus* present in Africa	Adapt specific cultural practices that conserve native natural enemies such as the predatory mirids (e.g. use only low-risk, or	Mirid augmentation in tomato greenhouses using commercial forms of the product (e.g. Mirical)	Work with international agencies to test candidate biological control agents

Method	Availability in Africa	Recommendations for open field tomato smallholders	Recommendations for commercial farms	Recommendations for government
	Nesidiocoris tenuis commercially available as biocontrol agent in some countries Native parasitoids present in Africa, but parasitism typically low Candidate agent for classical biological control still under screening in quarantine in Africa	species-specific pest control products) Maintain crop diversity comprising suitable wild plants that are hosts of the predators, to allow the natural enemy to persist in the environment when the presence of prey is low. Such plants provide refuge, food and alternative prey throughout the year during and at the end of crop cycles Agroecosystem management using companion plants, grown on the field edge or intercropped with tomato to enhance mirid activity (e.g. sesame)	Start introducing the predator a few weeks after seedling transplanting to allow build-up of a consistent population before the pest outbreak For *N. tenuis*, release of predator within seedling nurseries, so that when tomato plants are transplanted in the screenhouse they already carry the eggs of the predators	Support community production of biological control agents Explore the possibility of classical biological control through the introduction of specific parasitoids from South America
Host plant resistance	Resistance being pursued in breeding programmes for exploitation within IPM; *Bt* tomato under research	Use varieties if/when recommended that provide some resistance/tolerance, including short duration varieties that can escape the pest	Use short duration varieties where appropriate	Facilitate multiplication of any current varieties showing resistance Incorporate resistance to *Tuta absoluta* in breeding programmes Provide a framework for the regulation of *Bt* tomato varieties
Mating disruption	Not available in Africa	Ineffective in preventing economic losses when applied in the open field or unscreened greenhouses	Applying 30–60 g of pheromone per hectare in greenhouse tomato can control the moth populations, reduce the percentage of damaged fruits, and reduce the number of sprays	Provide temporary registration for products already registered in Europe and South America for this pest
Integrated pest management	Many available but largely ineffective when used as sole method	Destroy infested leaves and fruit by burying deep in the soil	If planting over a large area, synchronize planting as far as possible	Carry out research on integration of options listed for smallholders

Method	Availability in Africa	Recommendations for open field tomato smallholders	Recommendations for commercial farms	Recommendations for government
		Avoid growing tomato during late dry season Destroy old crops of suitable solanaceous hosts, especially eggplant, to slow down build-up of the pest Check for the presence of mines on the middle third of the tomato plant and pluck off the infested leaves. This can reduce the subsequent fruit damage Use non-chemical methods wherever possible for all pests of tomato Use agronets/net houses	Plant promptly Maintain good records of agronomy, monitoring, interventions, yield etc and review regularly	

4. Advice, information and communication

4.1 Sources of information on *Tuta absoluta* control

As part of the household survey with smallholder farmers in Kenya and Zambia, we analysed the sources of information on *Tuta absoluta* identification and control methods (Table 20). Neighbours, friends and family are the main sources of information (34.5% in Kenya; 41.8% in Zambia). Many farmers also obtain information from agro-dealers and input suppliers (30.8% in Kenya; 22.8% in Zambia), which suggests that this could be a main pathway for information dissemination as farmers procure highly toxic pesticides from agro-dealers. We also found that in Zambia, government extension workers continue to play an important role in information dissemination (40.4%). Plant clinics are important as a source of information in Kenya (15.5%), but less so in Zambia (3.1%). Across both countries, there is still a low uptake of e-extension services, using SMS and smartphones (>1% of respondents) or internet (between 1.2% - 3.8%).

Table 20: Sources of information on *Tuta absoluta* identification and control methods

Source	Kenya % (n=400)	Zambia % (n=426)
Neighbours, friends and family	34.5	41.8
Agro-dealers / input suppliers	30.8	22.8
Government extension officers	18.0	40.4
My own experience	15.8	20.7
Plant doctor / plant clinic	15.5	3.1
Lead farmer	14.8	4.9
Agricultural programmes on radio / TV	7.0	5.9
Internet	3.8	1.2
Magazine, newspaper	2.3	0.7
Farmer co-operative	1.5	3.3
Demonstration plots / field days / Farmer field school	1.5	0.9
Agricultural trade fairs	1.3	2.1
Mobile SMS and voice services	1.0	1.2
Others	0.5	2.4

4.2 Criteria for control advice

The criteria for control advice presented in this section are adapted from Abrahams *et al*. (2017), as these are relevant for any method for managing an invasive pest. Ideally, advice or recommendation on a method for managing *Tuta absoluta* should not be made without consideration of the following criteria. The PMDGs for *Tuta absoluta* that have been developed for Ethiopia, Kenya, Malawi, Tanzania, Uganda and Zambia provide some recommendations that should be followed as they are largely in line with the criteria below, although they need to be updated on a regular basis as new methods become available. Some countries, like Kenya, have detailed information on a wider range of methods for control of this pest than do other countries, probably because more products are registered for this pest. Although the majority of the pesticide recommendations in the PMDGs are Class II, III and U (some, like azadirachtin, have no WHO classification), the survey showed that Class I products are being used at farm level. Therefore, farmers may not be following all the recommendations.

We recommend the following criteria for control advice:

- **Efficacy.** This is often assumed to be the most important criterion, even if this is not stated explicitly. If a practice is to be recommended there should be some evidence that it will be effective in at least some situations. Where a product has to be registered, this generally includes demonstration of efficacy, but many IPM practices do not involve a registered product. Results from controlled trials in an appropriate context are desirable, though not always available.
- **Safety.** Even registered products can be hazardous to human health without precautions. Safety should thus be considered based on a consideration of how the product is likely to be used rather than whether recommended safety precautions are adequate. Some practices not requiring registration can also be hazardous, such as some plant extracts.
- **Sustainability.** Possible effects on non-target organisms, such as pollinators, natural enemies and other organisms, should be considered. A control method may also have potential to create new problems, such as resurgence of other pests or pesticide resistance.
- **Practicality.** Some methods may be impractical for some farmers, particularly those requiring elaborate safety precautions. Others may be only practical at a small scale.
- **Availability.** Availability of regulated products is initially determined by their registration status, but even registered products may not be widely stocked if distribution is expensive and/or the perceived market is small. Unregulated inputs for some control methods may not be easily available, such as seeds of companion plants.
- **Cost-effectiveness.** At the simplest level the cost of control must be less than the value of crop loss avoided, for it to be worthwhile. Opportunity and other costs may need to be considered.

In practice, many of these criteria are context-specific, so recommendations and advice are unlikely to suit all farmers in all situations. This highlights different underlying approaches to the role of advisory services. The linear “transfer of technology” approach emphasizes prescriptive advice on the use of new technologies. Participatory approaches emphasize educating and empowering farmers to use information and experience to make their own choices. Both approaches have advantages and disadvantages.

4.3 Communication channels

The communications methods presented in this section are also adapted from Abrahams *et al*. (2017), as they are relevant for communication targeting a new invasive pest. Many different methods can be used to communicate with farmers and other stakeholders (see

Table 20). Different channels have different advantages and disadvantages, the following being some of the factors to consider when using a particular approach:

- *Outreach speed.* Some channels enable information to reach users very rapidly, while others are slower. Rapid outreach might be required to ensure information is timely.
- *Numbers reached.* Some communication channels, particularly the mass media, can reach much larger numbers than other methods.
- *Cost.* One measure of cost is the marginal cost per person reached with a particular message. Some channels have much higher start-up costs than others.
- *Complexity of messages*. Complex messages are best communicated when there is an opportunity for dialogue, such as face-to-face channels. Some mass media approaches can incorporate dialogue, such as radio phone-ins. IPM can be “knowledge intensive”, which is why farmer field schools are particularly appropriate for promoting IPM.
- *Audience*. Different channels may be more or less suitable for different audiences, such as men, women or youth. It is also important to consider language.

Often a trade-off is required between these different factors, so in practice an effective communication campaign is likely to require a combination of approaches.

4.4 Information resources and tools

CABI has launched a *Tuta absoluta* Portal (https://www.cabi.org/ISC/tuta), as an integral part of its open access Invasive Species Compendium. The portal includes a wide variety of information for farmers, policy makers, researchers and other stakeholders, collated from multiple sources.

A large volume of materials and resources on *Tuta absoluta* are also available on the *Tuta absoluta* information network (http://www.tutaabsoluta.com/tuta-absoluta)

Invasive species compendium: this is a free encyclopaedic resource that brings together a wide range of different types of science-based information to support decision making in invasive species management worldwide (www.cabi.org/isc).

Crop protection compendium: this is an encyclopaedic resource that brings together a wide range of different types of science-based information on all aspects of crop protection. It comprises detailed datasheets on pests, diseases, weeds, host crops and natural enemies (https://www.cabi.org/cpc).

5. Recommendations

Tuta absoluta will undoubtedly continue to be an important pest of tomatoes and, possibly, other Solanaceae in many African countries. For the moment, the management of the pest relies nearly exclusively on the intensive use chemical insecticides, some of which are highly toxic. Awareness should be raised on the dangers of these pesticides, for farmers, consumers and the environment. Such practices will also undoubtedly result in insecticide resistance, which is commonly observed in South America and Europe, and probably already occurs in Africa. To avoid side effects of the intensive use of pesticides and to lower the risk of insecticide resistance, sustainable IPM strategies, based on biological control whenever possible, urgently need to be developed for different regions in Africa. This includes, for example, the following:

High-level policy makers:

- make informed, science-based decisions at national level to protect biodiversity, consumers and trade from indiscriminate pesticide use
- conduct a study on the health and environmental impacts in the country of high pesticide use on tomatoes
- develop a technical guidance standard for pesticides use in tomatoes: covering procurement, risk reduction and resistance management
- lobby for budgetary allocation from national governments to subsidize the cost of low-risk options for managing *Tuta absoluta*
- provide incentives to industry associations that are involved in the production and sale of lower-risk products for *Tuta absoluta*

Regulators:

- officially report to the International Plant Protection Convention if the pest is already present within the borders of the country
- identify unregistered and/or highly hazardous products being used for *Tuta absoluta* and regulate their distribution and use
- facilitate the registration and promotion of lower-risk products for *Tuta absoluta*, including biopesticides, botanicals and pheromones, and the use of natural enemies through augmentative biological control
- explore with research agencies the use of classical biological control for *Tuta absoluta* using host-specific parasitoids from South America

Researchers:

- carry out rapid testing of new active ingredients of pesticides for their modes of action and low environmental impact, including lethal and sub-lethal effects on field populations of beneficial arthropods, recognizing that farmers will continue to use such products in the foreseeable future
- test locally available biopesticides and botanicals, particularly essential oils, and produce formulations that maximize the toxic effect on *Tuta absoluta* and reduce side effects on beneficial arthropods
- carry out surveys for local natural enemies that can be used in augmentative biological control, such as predatory mirid bugs and *Trichogramma* spp. egg parasitoids, which have been successfully used elsewhere

- establish the economic considerations for control methods, such as augmentation and the use of conservation biological control
- exploit companion plants to improve the conservation and the effectiveness of predators and parasitoids; augment parasitoids; and disrupt mating
- test a model for the production of biological agents at community level

Advisory services:

- communicate to farmers using various communication approaches about the negative impacts of indiscriminate pesticide use on their health and the environment
- consider efficacy, safety, sustainability, practicality, availability and cost-effectiveness when recommending control practices
- encourage farmers to integrate highly selective low-risk pest control products with biological control within a holistic IPM strategy

Smallholder farmers:

- carry out pest monitoring to determine the threshold levels either for the timing of control, or for making a decision whether or not remedial action is to be taken. A spray regime based on a programme is not recommended
- use only pesticides recommended by the government, and choose those that are lower-risk or selective insecticides if available/affordable, to protect mirid predators
- use proper PPE when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product
- consider using homemade products made from plants known to have a pesticidal effect
- adapt specific cultural practices that conserve native natural enemies
- use short duration varieties whenever appropriate

Commercial farmers:

- the spray regime for pesticides should be based on an action threshold that takes into consideration the expected value of the crop, the expected loss if untreated, and the cost of treatment
- farm workers should use the proper PPE when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product
- assess the efficacy of other products if available, and adopt for use
- augment predatory mirids in tomato greenhouses using commercial forms of the product where these are commercially available
- maintain good records of agronomy, monitoring, interventions, yield etc and review regularly to determine the cost benefit of the control methods used

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