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Arthropod pest complex and associated damage in field-grown tomato in Senegal

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Abstract. Biotic factors (including insect pests) constrain field-grown tomato production in Senegal. However, little information is available on the identity and life system of key pests. The objectives of this study were to: (i) update key pest records of field-grown tomato in the central vegetable-producing area along the northern coast of Senegal, known as the Niayes area; (ii) map their spatial and temporal incidence and (iii) understand insecticide use by growers to control the pests. A total of 98 tomato fields distributed in three zones along a north–south transect in the Niayes area were monitored over four crop cycles from 2012 to 2014. As expected, the tomato fruitworm *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae) was the most destructive pest with an occurrence of 92% in sampled fields (90/98) and up to 38% damaged fruits in one field at the time of sampling. The proportion of damaged fruits did not differ among zones, but was significantly higher in the early dry season compared to the late dry season. The invasive tomato leafminer *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) was detected in 53% of sampled fields (52/98), mainly in the south of the Niayes area in the late dry season. Because of their ability to adapt to unstable environment and insecticides, this insect pest assemblage is a new challenge that farmers have to deal with while decreasing their use of broad-spectrum insecticides.

Key words: Integrated pest management, biological invasion, incidence, damage, *Tuta absoluta*, *Helicoverpa armigera*, host range, horticulture, Africa

Introduction

In sub-Saharan Africa, horticulture is a promising driver of economic growth, as it is a vital source of income for resource-poor growers in rural and peri-urban areas (Moustier, 2007; van Veenhuizen and Danso, 2007; Labaste, 2007). Furthermore, fruit and vegetable crops can contribute to food security and nutritional balance for most vulnerable populations (FAO, 2012). In Senegal, the field-grown tomato is one of the most important crops of the horticultural value chain. Tomato production increased from 40,000 to 190,000 tons between 2000 and 2013 to meet growing urban demand

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for fresh market tomato and processing (FAO, 2015). However, the continuous yield and quality of tomato production is threatened by significant biotic constraints, including serious diseases, such as bacterial wilt caused by *Ralstonia solanacearum* (Smith) (N'Guessan *et al.*, 2012), nematodes (Netscher, 1970; Diop *et al.*, 2000), mites (Huat, 2006) and insect pests causing direct damage or transmitting diseases (James *et al.*, 2010). Principal economic losses are due to insect pests, such as the fruitworm *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae) (Collingwood and Bourdouxhe, 1980), leafminer flies, particularly *Liriomyza trifolii* Burgess (Diptera: Agromyzidae) (Neuenschwander *et al.*, 1987) and the whitefly *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) that can transmit *Tomato yellow leaf curl virus* (TYLCV) (D'Hondt and Russo, 1985; Camara *et al.*, 2013). The recent introduction of the invasive South American tomato leafminer *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a new challenge that farmers are facing (Pfeiffer *et al.*, 2013). *Tuta absoluta* that is also known as the South American tomato pinworm can attack tomato plants at any developmental stage. *Tuta absoluta* larvae mine on leaves and bore holes on stems and fruits, negatively affecting crop yield and fruit quality. The threat to agricultural production due to *T. absoluta* invasion may include other significant crops from the family Solanaceae, such as potato (Desneux *et al.*, 2011; Tropea Garzia *et al.*, 2012). Previous results showed that *T. absoluta* populations were established across the central vegetable-producing area of Senegal, the Niayes, which is located along the northern coast, where growers abandoned fields as a result of crop damage during 2012/13 season (Brévault *et al.*, 2014).

In less developed countries, losses caused by crop pests along the value chain of agricultural production remain high, and threats are set to increase with climate change (Maxmen, 2013). Most farmers lack suitable alternatives to broad-spectrum chemicals to effectively control insect pests (Sam *et al.*, 2014). Intensive use of the same class of insecticides often leads to the evolution of insect resistance (Martin *et al.*, 2005; Brévault *et al.*, 2008; Djihinto *et al.*, 2009; Houndété *et al.*, 2010), and to severe hazards for the ecosystem and human health (Barzman *et al.*, 2015). Besides, detrimental effects on biodiversity can result in pest outbreaks due to the alteration of ecosystem services, such as natural pest regulation provided by natural enemies (Desneux *et al.*, 2007; Power, 2010; Biondi *et al.*, 2012; Grzywacz *et al.*, 2014). Development of new pest management strategies is needed to minimize the use of pesticides and preserve natural resources (De Bon *et al.*, 2014). New pest management strategies require better science-based knowledge on the identity and life system of key pests, including spatial distribution and seasonal occurrence.

The current study aimed to: (i) update key pest records of field-grown tomato in the central vegetable-producing area in Senegal, the Niayes; (ii) map their spatial and temporal incidence and (iii) characterize insecticides used by growers to control key pests. Field surveys were conducted from 2012 to 2014 on a set of 98 tomato fields. Our results are useful for developing essential guidelines for improving pest management strategies, from local to regional practices, in the framework of sustainable vegetable production systems.

Materials and methods

Field sites

A survey was carried out in the Niayes ecoregion in Senegal (Fig. 1). The Niayes area is located along the northern coast on a 180 km coastal strip 10–30 km wide. Dunes and depressions that are often flooded characterize the environment and the alternation of a short wet season (July–September) and a long dry season (October–June) during which most vegetable crops are grown under irrigation. This horticultural area provides about 80% of domestic vegetable production.

A set of 98 fields was selected in 3 zones of the Niayes area along a north–south transect from Dakar to Saint-Louis (Fig. 1). Surveys were carried out over two dry seasons and two consecutive crop cycles per season, from October 2012 to May 2014 (Fig. 1). For each crop cycle, sampled fields were separated by at least 2 km from each other. Temperature was recorded for each zone using data loggers (Hobo, Prosensor) placed throughout the crop cycle in two sampled fields.

Pest monitoring

Sampling of arthropod pests in sampled tomato fields was carried out every three weeks from transplanting to harvest. For each field, 24 tomato plants were randomly selected and classified according to their phenological stage (vegetative, flowering, fruiting and maturity). The entire plant was observed in the field by eye for symptoms of nematodes (symptomatic plants checked for galls on roots), diseases, especially TYLCV (CABI, 2013), and fruit damage. Three leaves per plant (from lower, intermediate and upper canopy) were inspected for the presence of arthropod pests or associated damage. Insect specimens were collected and conserved in 70% ethanol for further identification in the laboratory with the help of

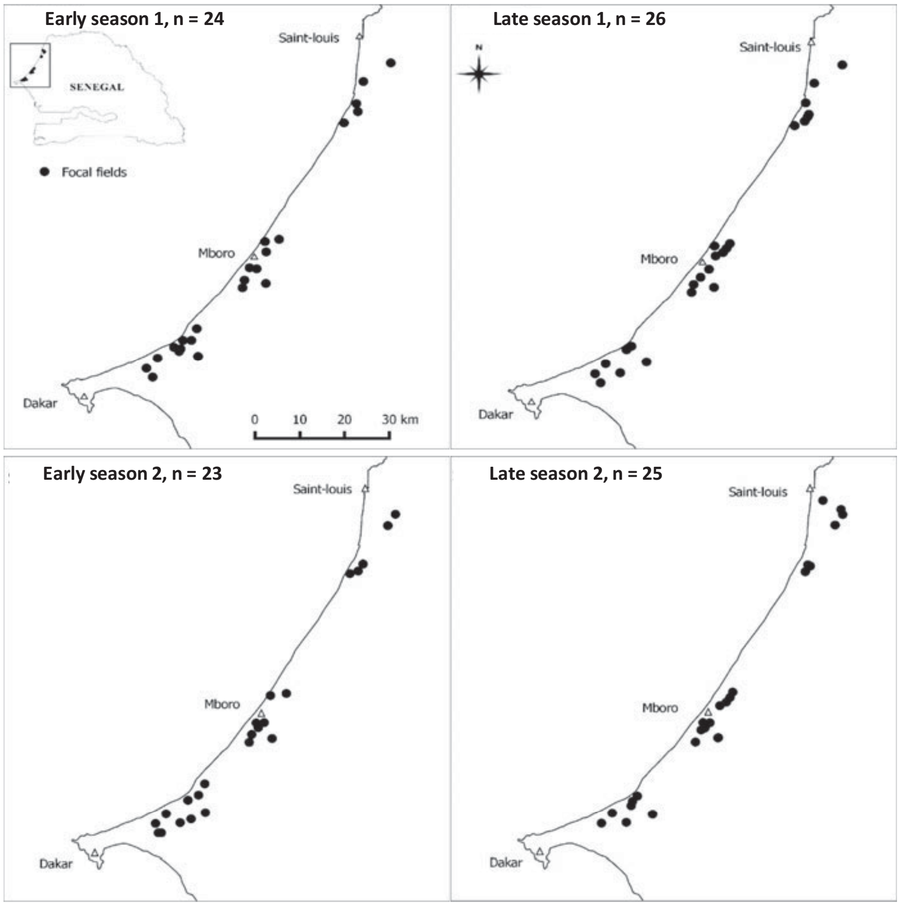

Fig. 1. Spatial distribution of sampled tomato fields in the Niayes area over two dry seasons (season 1 [2012/2013] and season 2 [2013/2014]) and two crop cycles (early and late dry season) per season.

fact sheets and taxonomic keys for arthropod identification (Delvare and Aberlenc, 1989; Bordat and Arvanitakis, 2004; James *et al.*, 2010) and insect taxonomists (G. Delvare and D. Bordat, CIRAD, France) when necessary. 'Occurrence' refers here to proportion of infested fields. 'Incidence' indicates proportion of infested plants (or leaves). A set of fields of potential host crops adjacent to the sampled fields were inspected once for presence of *H. armigera* larvae on 24 randomly selected plants. These included Solanaceae: sweet pepper *Capsicum frutescens* L., eggplant *Solanum melongena* L., potato *S. tuberosum* L., Ethiopian eggplant *S. aethiopicum* L. and pepper *Capsicum annuum* L.; Brassicaceae: cabbage *Brassica oleracea* L. var. *capitata* and turnip *Brassica rapa* L.; Cucurbitaceae: squash *Cucurbita maxima* L. and zucchini *Cucurbita pepo* L.; Asteraceae: lettuce *Lactuca sativa* L.; and Alliaceae: onion *Allium cepa* L. A farmers' survey of insecticide applications (date, trade mark, active ingredient) was conducted for each sampled field during the entire crop cycle.

Statistical analyses

The effect of zone (south, centre, north), season (2012/2013, 2013/2014), crop cycle (1–4) and crop phenology on the incidence (proportion of infested plants) of arthropod pests was assessed using logistic regression assuming a binomial distribution of the data (GLM logit function). The effect of the explanatory variables was assessed using a type II analysis with the criterion of maximum likelihood ratio. Mean comparisons were done using Tukey pair-wise comparisons. Graphical representations of data as box plots were done to give information on the central tendency values (mean and median), their variability, symmetry of distribution and the presence of atypical values. Non-parametric Kruskal–Wallis tests were carried out to assess the effect of zone and 'insecticide use' groups on the number of insecticide applications and the effect of 'insecticide use' groups on the incidence of *H. armigera* and *T. absoluta* in sampled fields. An analysis of variance (ANOVA) was used to

Table 1. Incidence of arthropod pests observed on tomato fields ($N = 98$) in the Niayes area over two cropping seasons, from October 2012 to May 2014

Order	Family	Species	Variable (%)	Mean	Max
Lepidoptera	Noctuidae	*Helicoverpa armigera*	Occurrence	91.8	
			Infested leaves	1.3	5.9
			Damaged fruits	4.9	28.2
	Gelechiidae	*Tuta absoluta*	Occurrence	53.1	
			Infested leaves	4.6	59.7
Diptera	Agromyzidae	*Liriomyza* spp.	Occurrence	82.7	
			Infested leaves	4.0	22.9
Hemiptera	Aleyrodidae	*Bemisia tabaci*	Occurrence	44.9	
			Infested leaves	1.9	24.1
			TYLCV occurrence	9.2	
			TYLCV-infected plants	3.6	58.8
	Aphididae		Occurrence	10.2	
			Infested leaves	0.2	11.1
	Miridae		Occurrence	11.2	
			Infested leaves	0.1	2.4
	Cicadellidae	*Empoasca* spp.	Occurrence	9.2	
			Infested leaves	0.0	0.7
Acari	Tetranychidae	*Tetranychus* spp.	Occurrence	15.3	
			Infested plants	0.6	25.0

Occurrence: proportion of infested fields.

test the effect of season, time of season and zone on temperature. Analyses were performed with XLSTAT Version 2015.1.01 (Addinsoft).

Results

Temperature across zones

Mean temperatures during field monitoring were 24.3, 22.4, 22.7 and 21.7 °C for crop cycles 1, 2, 3 and 4, respectively. Season 1 was warmer (+1.1 °C) than season 2 ($F = 7.9$, df = 1, $P<0.01$). The first part of the dry season was warmer (+1.3 °C) than late part of the dry season ($F = 14.0$, df = 1, $P<0.001$). No significant temperature difference was recorded among zones ($F = 0.8$, df = 2, $P = 0.431$). No effect of zone or time of season on minimum temperature was observed ($F = 0.0$, df = 2, $P = 0.994$ and $F = 0.6$, df = 1, $P = 0.447$, respectively). Maximum temperature was higher in the north zone than in the south (+2.9 °C) and centre (+3.9 °C) zones ($F = 11.0$, df = 2, $P<0.001$), and higher (+1.5 °C) during the first part of the dry season ($F = 4.7$, df = 1, $P = 0.032$).

Incidence of key insect pests

The tomato fruit worm *H. armigera* was the major pest with an occurrence of 91.8% in sampled fields and up to 38.2% damaged fruits at the time of sampling (Tables 1 and 2). *Helicoverpa armigera* larvae were observed on tomato leaves before the flowering stage (before 21 days post planting) and their abundance slightly increased at early flowering ($\chi^2 = 27.7$, df = 4, $P<0.001$). Fruit damage started as soon as early fruiting and significantly increased during the fruiting stage ($\chi^2 = 185.1$, df = 3, $P<0.001$). An average of 8.6% damaged fruits with a maximum of 23.0% damaged fruits in one field were observed at harvest time.

Typical leaf damage caused by the tomato leafminer *T. absoluta* (Wyckhuys *et al.*, 2012) was observed in 53.1% of the sampled fields, with an average of 4.6% infested leaves, and a maximum of 59.7% in one sampled field (Table 1, Fig. 2). The tomato leafminer *T. absoluta* colonized tomato plants at the vegetative stage, before reaching a maximum at the early fruiting stage ($\chi^2 = 99.9$, df = 4, $P<0.001$). A maximum of 87.5% mined leaves were observed in one field (Table 2).

Damage due to leafminer flies *Liriomyza* spp. was also observed in sampled fields (82.7%). However, mean proportion of infested leaves was only 4.0%, with a maximum of 22.9% in one field. Mines were observed on plant seedlings, resulting in significant incidence in some fields from the vegetative to early fruiting stage (29.2–45.8% infested leaves). Whiteflies *B. tabaci* were observed on less than half of the sampled fields (44.9%) at low densities (on average 1.9% infested leaves). Outbreaks of TYLCV were recorded in some fields (8/98), with up to 100% of plants infected during field monitoring. Incidence of *B. tabaci* was greater during the vegetative and early flowering stages ($\chi^2 = 167.5$, df = 4, $P<0.001$) of tomato plants, with a maximum of 70.8% infested

Table 2. Incidence of key insect pests in tomato fields as a function of crop phenology

Species *Lycopersicon esculentum*	Variable (%) Stage		Days post transplanting+ 0–20 Vegetative	21–40 Early flowering	41–60 Fruiting	61–80 Fruiting	>80 Harvest
Helicoverpa armigera	Occurrence		21.1 d	46.7 c	73.6 b	86.0 ab	100 a
	Infested leaves	Mean	0.7 b	1.4 a	1.5 a	1.7 a	0.2 b
		Max.	11.1	11	14	10	2.8
	Damaged fruits	Mean		1.2 d	3.7 c	7.4 b	8.6 a
		Max.		14.8	33.9	38.2	23.0
Tuta absoluta	Occurrence		23.9	30.0	39.1	24.5	28.6
	Infested leaves	Mean	2.8 c	3.2 c	5.7 a	4.2 b	0.5 d
		Max.	59.7	52.8	87.5	75.0	80.0
Liriomyza spp.	Occurrence		53.5	58.9	50.6	41.5	28.6
	Infested leaves	Mean	4.2	4.3	4.0	3.7	2.6
		Max.	29.2	38.9	45.8	38.9	16.7
Bemisia tabaci	Occurrence		28.2 a	31.1 a	18.4 ab	5.7 b	7.1 b
	Infested leaves	Mean	3.2 b	4.1 a	0.8 c	0.1 c	0.1 c
		Max.	54.2	70.8	18.1	1.4	1.4

Occurrence: percentage of infested fields. Data with different letters in the same row are not significantly different according to Tukey's test (P>0.05).
+Tomato plants were usually transplanted after four weeks in the nursery.

Fig. 2. *Tuta absoluta* adult (top, left) and larva (top, right), and damage caused by larvae on tomato leaves (bottom, left) and fruits (bottom, right).

leaves in one field. We found a low incidence of aphids, mirids, leafhoppers and mites (Table 1).

Spatio-temporal incidence of the tomato fruitworm

Incidence of the tomato fruitworm *H. armigera* in terms of fruit damage did not significantly vary among monitored zones (χ^2 = 5.8, df = 2, P = 0.410) (Fig. 3A). Fruit damage due to the tomato fruit worm was greater during the early dry season compared to the late dry season (χ^2 = 179.1, df = 1, $P<0.001$) (Fig. 3B). Fruit damage was greater in season 1 than in season 2 ($\chi^2 = 86.8$, df = 1, $P<0.001$). Significant damage caused by *H. armigera* larvae was

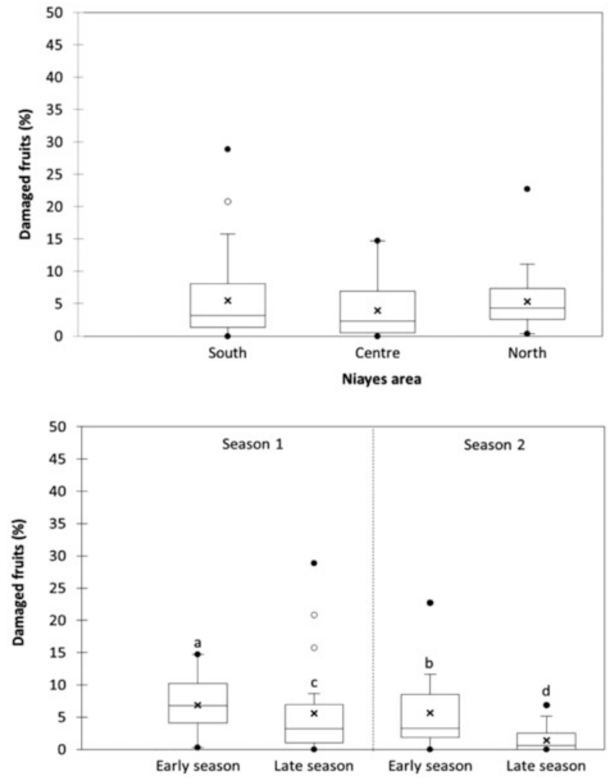

Fig. 3. Incidence of the tomato fruitworm *Helicoverpa armigera* for (A) the zone in the Niayes area (2012/2013 and 2013/2014 seasons) and (B) season (2012/2013 and 2013/2014 seasons) and time of season (early [October to January] vs. late dry season [February to May]). Lower edge of the box represents the first quartile (Q1). Median is represented by the central line and mean by 'x'. The third quartile (Q3) corresponds to the upper edge of the box. Two gaps are defined on either side of the first and third quartiles: IQ1 = [Q1 − 1.5 × (Q3 − Q1) Q1] and IQ3 = [Q3, Q3 + 1.5 × (Q3 − Q1)]. Closed circles (•) represent the minimum and maximum values, while the open circles (○) represent extreme values above IQ1 and IQ3.

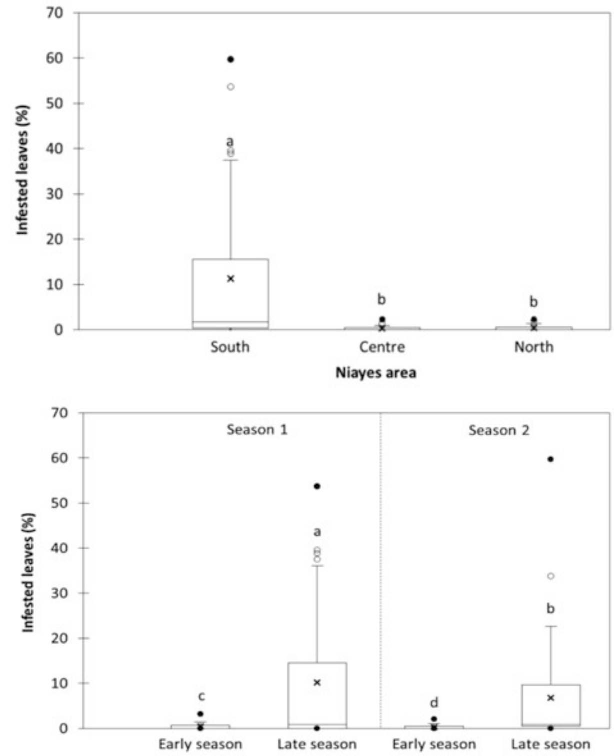

Fig. 4. Incidence of the tomato leafminer *Tuta absoluta* for (A) the zone in the Niayes area (2012/2013 and 2013/2014 seasons) and (B) the season (2012/2013 and 2013/2014 seasons) and time of season (early dry season [October to January] vs. late dry season [February to May]).

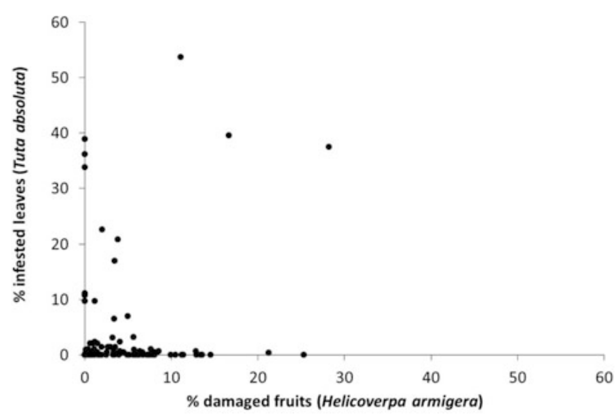

Fig. 5. Relationship between proportion of fruits damaged by *Helicoverpa armigera* and the number of leaves mined by *Tuta absoluta* in sampled tomato fields ($N = 98$).

observed on other vegetable crops, such as sweet pepper, eggplant and Ethiopian eggplant fruit, and cabbage head (Table 3). *Helicoverpa armigera* larvae were occasionally detected on leaves or flowers of other crops such as potato, pepper, turnip, squash, zucchini, lettuce and onion (Table 3).

Spatio-temporal incidence of the tomato leafminer

The incidence of the tomato leafminer *T. absoluta* was greater in the south zone of the Niayes area, with 0–60% mined leaves ($\chi^2 = 645.5$, df = 2, $P<0.001$) (Fig. 4A). The proportion of mined leaves was greater in season 1 than in season 2 ($\chi^2 = 62.8$, df = 1, $P<0.001$), and during the late dry season compared to the early dry season ($\chi^2 = 558.9$, df = 1, $P<0.001$) (Fig. 4B). No significant relationship was observed between incidence of *H. armigera* and that of *T. absoluta* in sampled fields ($r^2 = 0.02$, $P = 0.160$) (Fig. 5).

Table 3. Incidence of *Helicoverpa armigera* on other vegetable crops in the Niayes area

	Crop			
	Sweet pepper	Cabbage	Eggplant	Ethiopian eggplant
Monitored fields	34	116	56	17
Infested fields (%)	38.2	29.3	25.0	11.8
Infested plants (%)	3.6	0.8	1.7	0.7
Max. infested plants (%)	37.5	9.4	25.0	8.3

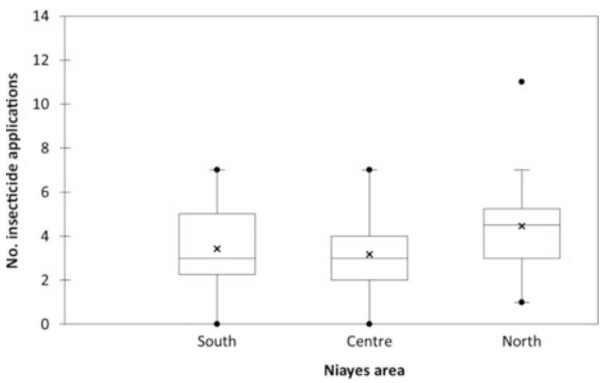

Fig. 6. Number of insecticide applications over a tomato crop cycle in the south, central and north zones in the Niayes area (2012/2013 and 2013/2014 seasons).

Insecticide use

The mean number of insecticide applications was 3.4, 3.2 and 4.5 over the crop cycle in the south, centre and north zones of the Niayes area, respectively. No significant difference between zones was observed ($K = 5.9$, df = 2, $P = 0.054$) (Fig. 6). The number of insecticide applications was significantly correlated to the proportion (log transformed) of fruit damage due to *H. armigera* ($r = 0.24$, $P = 0.019$) but not to the proportion of plants infested by *T. absoluta* ($r = -0.07$, $P = 0.508$). Most applications were made with broad-spectrum insecticides, including organophosphates, pyrethroid-based formulations (>60% of pyrethroid applications were binary or ternary formulations, including neonicotinoids or organophosphates) or avermectins (abamectin) (Fig. 7). A low proportion of insecticide applications (6%) was with biopesticides, including *Bacillus thuringiensis* or neem oil commercial formulations. Other insecticides included indoxacarb (oxadiazine), methomyl (carbamate), imidacloprid (neonicotinoid) and dicofol (organochlorine).

Discussion

Insect pests are a significant constraint to field-grown tomato production in Senegal (Collingwood and Bourdouxhe, 1980; Huat, 2006). The tomato fruitworm *H. armigera* remains the most widespread pest, as we detected larvae or associated damage in almost all sampled fields (90/98). Larvae were observed on leaves from the vegetative stage, and mostly from early flowering. Fruit damage started at the onset of the fruiting stage and significantly increased during fruiting. An average of 4.9% damaged fruits, with a maximum of 38.2%, was observed during crop growth. An average of 8.6% damaged fruits, with a maximum of 23.0%, was seen at harvest time. Incidence at harvest time does not include most fruits that were attacked at an early stage and rotted a few days later. The species was already reported to cause up to 85% fruit damage (Collingwood and Bourdouxhe, 1980). In field monitoring conducted in Nigeria in 2011/2012, Mailafiya *et al.* (2014) showed that *H. armigera* was the primary pest of tomato crops. In Spain, 3% damage during crop growth (seasonal damage) was proposed as an economic threshold in Integrated Pest Management (IPM) programmes to control *H. armigera* in processing tomato crops (Torres-Vila *et al.*, 2003).

Incidence of the tomato fruitworm did not differ among zones in the Niayes area. Fruit damage was greater in the early season, on the first crop cycle after the rainy season. Moths that colonize tomato crops could come from rainfed crops, including pearl millet, corn and cotton. Reverse migration could also occur from vegetable host crops to rainfed crops at the beginning of the rainy season (Brévault *et al.*, 2008; 2012). Higher temperature in season 1 compared to season 2 could partially explain the greater incidence of *H. armigera* in season 1.

Significant damage of *H. armigera* larvae was observed on other vegetable crops, such as sweet pepper, eggplant, Ethiopian eggplant and cabbage. The presence of larvae was occasionally detected on leaves or flowers of vegetable crops, such as potato, pepper, turnip, squash, zucchini, lettuce and onion. These observations confirm the high degree of polyphagy in *H. armigera* (CABI, 2016) and typical traits of an invasive species by its ability to adapt to changing environment, e.g. by broadening its ecological niche, by migrating or locally diapausing when resources are scarce or by evolving resistance when insecticide pressure is high (Cunningham and Zalucki, 2014). *Helicoverpa armigera* was recorded

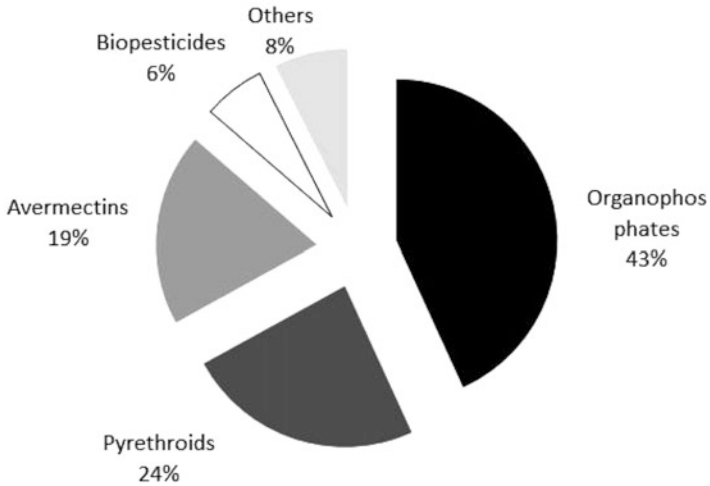

Fig. 7. Insecticide use by growers to manage insect pests in tomato sampled fields (relative to total number of insecticide applications, $N = 403$).

for the first time in Brazil in 2013 (Czepak *et al.*, 2013), where significant damage was observed on cotton and soybean crops, and also in Argentina in 2013 (Gabriela Murúa *et al.*, 2014). *Helicoverpa armigera* has a growing importance in Europe with crop damage and insecticide resistance (Mironidis *et al.*, 2013). A better understanding of genetic and demographic flows among agricultural production basins in Senegal, and more broadly in West Africa, is necessary for the development of area-wide pest management strategies (Brévault and Bouyer, 2014).

The invasive tomato leafminer *T. absoluta* was detected in more than half of sampled fields (52/98), mainly in the south zone of the Niayes area during the late dry season. As no significant difference in temperatures was observed among zones, it is probable that populations decrease during the rainy season, due to low resource availability (few solanaceous crops, particularly in the north and centre of Niayes) and rainfall (de Medeiros *et al.*, 2011). *Tuta absoluta* populations may start to grow at the early dry season, with larger populations southward in relation to the importance of solanaceous crops, and subsequent recolonization of the central and north zones by long-distance dispersal. A maximum of 87.5% mined leaves was observed in one field at fruiting. In some cases, growers were forced to abandon their fields due to uncontrollable outbreaks, as reported by Brévault *et al.* (2014). Colonization of tomato plants started at the vegetative stage just after transplanting, to reach a maximum during the flowering–fruiting stage, but infestations were also observed in nurseries (S. Sylla, unpublished data).

Incidence of *H. armigera* and *T. absoluta* populations was variable among sampled fields within the same zone. This suggests the important effect of crop management, particularly insecticide use, but possibly also in the landscape context, e.g. semi-natural habitats, which would favour biocontrol by natural enemies (Maalouly *et al.*, 2013; Morandin *et al.*, 2014), or diversity and abundance of host crops, which would affect their dynamics (Carrière *et al.*, 2012; Lu and Baker, 2013). In a previous study, Brévault *et al.* (2014) detected the presence of *T. absoluta* on other vegetable crops, such as eggplant and Ethiopian eggplant. No relationship was observed between the incidence of *H. armigera* and that of *T. absoluta* in sampled fields. This could suggest no competition for resources, though direct competition was expected between moths for oviposition on leaves, or between larvae (particulary early instars) for food, knowing the territorial behaviour of *H. armigera* larvae (Sigsgaard *et al.*, 2002; Kakimoto *et al.*, 2003). Relative low density of *H. armigera* larvae in tomato fields, location of larvae on leaves (abaxial vs. adaxial surface of the leaf), dissimilar effect of insecticide applications on the two species, or asynchronism of infestation (early vs. late season) could explain the lack of observed competition. Studies should be conducted at the plant level to better estimate interactions among species.

The occurrence of *Liriomyza* spp. was high but the proportion of infested leaves was low. Coly *et al.* (1993) reported significant crop losses of up to 41% and an average density of 111 larvae per plant. Whiteflies *B. tabaci* (Gennadius) were observed on less than half of sampled fields. Their presence, even at low densities, can however, cause significant losses due to transmission of viruses (up to 100% of plants infected with TYLCV). In Africa, whiteflies are often considered as the key insect pest of tomato crops (Umeh *et al.*, 2002; Gnankiné *et al.*, 2013). Aphids, mirids, leafhoppers or mites can be considered as secondary pests of field-grown tomato crops in the Niayes area.

Spraying of synthetic insecticides was the only method deployed by growers to control tomato pests. If the mean cumulative number of insecticide applications was moderate, with 3–4 treatments on average over the crop cycle, more than 5 insecticide applications were, however, carried out in 14 of 98 fields. Most growers use broad-spectrum insecticides, such as organophosphates, and to a lesser extent, pyrethroids (often in the form of binary or ternary products with neonicotinoids and organophosphates) and avermectins (abamectin). The repeated use of those insecticides, particularly organophosphates, is incompatible with the conservation of natural enemies and beneficial insects (Gentz *et al.*, 2010; Biondi *et al.*, 2013). Less than 5% of growers used biopesticides (*B. thuringiensis* and neem oil commercial formulations). The significant positive correlation (or the absence of significant correlation) observed between the number of insecticide applications and the incidence of *H. armigera* (or *T. absoluta*) indicates that insecticide strategies were not effective. Effective control of *T. absoluta* is generally difficult to achieve due to the endophytic behaviour of larvae (Lietti *et al.*, 2005; Desneux *et al.*, 2010), while populations of *H. armigera* have probably evolved resistance to some insecticides (Moreira *et al.*, 2002).

Conclusion

From this two-year field survey, we identified key insect pests of field-grown tomato in the main vegetable-producing area in Senegal, the Niayes. We also identified a new 'assemblage', which refers to a taxonomically related group (here, insect pests) of species (here, the highly polyphagous species *H. armigera* and the invasive species *T. absoluta*) that occur together in space and time according to the definition that Stroud *et al.* (2015) proposed. Because of their ability to adapt to changing environments (instability of resources, insecticide pressure, etc.), these two phytophagous lepidopterans are a major issue for crop protection. More research is needed to improve our knowledge on the life system of these two pests and drivers of their population dynamics. Crop losses due to these two key pests could result in the substantial increase of broad-spectrum insecticide use with economic and detrimental impact on the health of living organisms and ecosystems, in addition to the disruption of ongoing IPM initiatives. Capacity building of stakeholders to use selective insecticides, low doses, targeted applications (temporal or spatial), but also provision of bio-rational cost-effective insecticides (such as insect growth regulators [IGR] and biopesticides), should be also encouraged, to enhance biological control by indigenous natural enemies (Zappalà *et al.*, 2013). The results from this study could help develop guidelines for improving pest management strategies, from local to regional practices, in the framework of sustainable vegetable production systems. Coordinated efforts amongst stakeholders, research specialists and extension officers are needed to improve monitoring systems and to design area-wide management strategies.

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References

Barzman M., Bàrberi P., Birch A. N., Boonekamp P., Dachbrodt-Saaydeh S., Graf B., Hommel B., Jensen J. E., Kiss J., Kudsk P., Lamichhane J. R., Messéan A., Moonen A.-C., Ratnadass A., Ricci P., Sarah J.-L. and Sattin M. (2015) Eight principles of integrated pest management. *Agronomy for Sustainable Development* 35, 1199–1215.

Biondi A., Mommaerts V., Smagghe G., Viñuela E., Zappalà L. and Desneux N. (2012) The non-target impact of spinosyns on beneficial arthropods. *Pest Management Science* 68, 1523–1536.

Biondi A., Zappalà L., Stark J. D. and Desneux N. (2013) Do biopesticides affect the demographic traits of a parasitoid wasp and its biocontrol services through sublethal effects? *PLoS ONE* 8(9), e76548. Available at https://doi.org/10.1371/journal.pone.0076548

Bordat D. and Arvanitakis L. (2004) *Arthropodes des Cultures Légumières d'Afrique de l'Ouest, Centrale, Mayotte et Réunion*. CIRAD, Montpellier, France. 291 pp.

Brévault T. and Bouyer J. (2014) From integrated to system-wide pest management: Challenges for sustainable agriculture. *Outlooks on Pest Management* 25, 212–213.

Brévault T., Achaleke J., Sougnabé S. P. and Vaissayre M. (2008) Tracking pyrethroid resistance in the polyphagous bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae), in the shifting landscape of a cotton-growing area. *Bulletin of Entomological Research* 98, 565–573.

Brévault T., Nibouche S., Achaleke J. and Carrière Y. (2012) Assessing the role of non-cotton refuges in delaying *Helicoverpa armigera* resistance to Bt cotton in West Africa. *Evolutionary Applications* 5, 53–65.

Brévault T., Sylla S., Diatte M., Bernadas G. and Diarra K. (2014) *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae): A new threat to tomato production in sub-Saharan Africa. *African Entomology* 22, 441–444.

CABI (2013) Invasive species compendium. Available at http://www.cabi.org/isc/datasheet/55402

CABI (2016) Invasive species compendium. Available at http://www.cabi.org/isc/datasheet/26757

Camara M., Mbaye A. A., Noba K., Samb P. I., Diao S. and Cilas C. (2013) Field screening of tomato genotypes for resistance to tomato yellow leaf curl virus disease in Senegal. *Crop Protection* 44, 59–65.

Carrière Y., Goodell P. B., Ellers-Kirk C., Larocque G., Dutilleul P., Naranjo S. E. and Ellsworth P. (2012) Effects of local and landscape factors on population dynamics of a cotton pest. *PLoS ONE* 7, e39862.

Collingwood E. F. and Bourdouxhe L. (1980) Trials with decamethrin for the control of *Heliothis armigera* on tomatoes in Senegal. *International Journal of Pest Management* 26, 3–7.

Coly E. V., Bordat D. and Letourmy P. (1993) Incidence des dégâts de *Liriomyza trifolii* (Burgess) sur le rendement des cultures de haricot et de tomate dans les conditions du Sénégal, pp. 87–92. In *Conference on Leafmining Flies in Cultivated Plants*. CIRAD, Montpellier, France.

Cunningham J. P. and Zalucki M. P. (2014) Understanding heliothine (Lepidoptera: Heliothinae) pests: What is a host plant? *Journal of Economic Entomology* 107, 881–896.

Czepak C., Albernaz K. C., Vivan L. M., Guimarães H. O. and Carvalhais T. (2013) First reported occurrence of *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) in Brazil. *Pesquisa Agropecuária Tropical* 43, 110–113.

De Bon H., Huat J., Parrot L., Sinzogan A., Martin T., Malézieux E. and Vayssières J. F. (2014) Pesticide risks from fruit and vegetable pest management by small farmers in sub-Saharan Africa. A review. *Agronomy for Sustainable Development* 34, 723–736.

Delvare G. and Aberlenc H. P. (1989) *Les Insects d'Afrique et d'Amérique Tropicale: Clés Pour la Reconnaissance des Familles*. CIRAD, Montpellier, France. 302 pp.

de Medeiros M. A., Sujii E. R. and de Morais H. C. (2011) Mortality factors at egg stage of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on organic tomato system and on conventional tomato system. *Bragantia* 70, 72–80.

Desneux N., Decourtye A. and Delpuech J.-M. (2007) The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology* 52, 81–106.

Desneux N., Wajnberg E., Wyckhuys K. A. G., Burgio G., Arpaia S., Narváez-Vasquez C. A., González-Cabrera J., Ruescas D.C., Tabone E., Frandon J., Pizzol J., Poncet C., Cabello T. and Urbaneja A. (2010) Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. *Journal of Pest Science* 83, 197–215.

Desneux N., Luna M. G., Guillemaud T. and Urbaneja A. (2011) The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production. *Journal of Pest Science* 84, 403–408.

D'Hondt M. D. and Russo M. (1985) Tomato yellow leaf curl in Senegal. *Journal of Phytopathology* 112, 153–160.

Diop M. T., Ndiaye S., Mounport D. and Mateille T. (2000) Development of *Meloidogyne javanica* and *Scutellonema cavenessi* populations in vegetable crop systems in Senegal. *Nematology* 2, 535–540.

Djihinto A. C., Katary A. K., Prudent P., Vassal J.-M. and Vaissayre M. (2009) Variation in resistance to pyrethroids in *Helicoverpa armigera* from Benin Republic, West Africa. *Journal of Economic Entomology* 102, 1928–1934.

Food and Agriculture Organization of the United Nations (2012) *Growing Greener Cities in Africa: First Status Report on Urban and Peri-urban Horticulture in Africa*. Food and Agriculture Organization of the United Nations, Rome, Italy. 111 pp.

Food and Agriculture Organization of the United Nations (2015) *FAOSTAT Database*. Accessed 25 June 2015. Available at: http://faostat3.fao.org/home/E

Gabriela Murúa M., Scalora F. S., Navarro F. R., Cazado L. E., Casmuz A., Villagrán M. E., Lobos E. and Gastaminza G. (2014) First record of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Argentina. *Florida Entomologist* 97, 854–856.

Gentz M. C., Murdoch G. and King G. F. (2010) Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. *Biological Control* 52, 208–215.

Gnankiné O., Ketoh G. and Martin T. (2013) Dynamics of the invasive *Bemisia tabaci* (Homoptera: Aleyrodidae) Mediterranean (MED) species in two West African countries. *International Journal of Tropical Insect Science* 33, 99–106.

Grzywacz D., Stevenson P. C., Mushobozi W. L., Belmain S. and Wilson K. (2014) The use of indigenous ecological resources for pest control in Africa. *Food Security* 6, 71–86.

Houndété T. A., Ketoh G., Hema O. S. A., Brévault T., Glitho I. A. and Martin T. (2010) Insecticide resistance in field populations of *Bemisia tabaci* (Hemiptera: Aleyrodidae) in West Africa. *Pest Management Science* 66, 1181–1185.

Huat J. (2006) Limitative factors of yields in factory-growing tomato fields in Northern Senegal. *Cahiers Agricultures* 15, 293–300.

James B., Atcha-Ahowé C., Godonou I., Baimey H., Georgen G., Sikirou R. and Toko M. (2010) *Integrated Pest Management in Vegetable Production: A Guide for Extension Workers in West Africa*. International Institute for Tropical Agriculture, Ibadan, Nigeria, 120 pp.

Kakimoto T., Fujisaki K. and Miyatake T. (2003) Egg laying preference, larval dispersion, and cannibalism in *Helicoverpa armigera* (Lepidoptera: Noctuidae). *Annals of the Entomological Society of America* 96, 793–798.

Labaste P. (Ed.) (2007) Le marché européen des produits horticoles: opportunités pour les exportateurs d'Afrique subsaharienne. World Bank working paper No. 63. Washington DC. Accessed 21 June 2016. Available at http://documents.worldbank.org/curated/en/2007/01/7746566

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

Lu Z. Z. and Baker G. (2013) Spatial and temporal dynamics of *Helicoverpa armigera* (Lepidoptera, Noctuidae) in contrasting agricultural landscapes in northwestern China. *International Journal of Pest Management* 59, 25–34.

Maalouly M., Franck P., Bouvier J.-C., Toubon J.-F. and Lavigne C. (2013) Codling moth parasitism is affected by semi-natural habitats and agricultural practices at orchard and landscape levels. *Agriculture, Ecosystems & Environment* 169, 33–42.

Mailafiya D. M., Degri M. M., Maina Y. T., Gadzama U. N. and Galadima I. B. (2014) Preliminary studies on insect pest incidence on tomato in Bama, Borno State, Nigeria. *International Letters of Natural Sciences* 5, 45–54.

Martin T., Ochou G. O., Djihinto A., Traoré D., Togola M., Vassal J. M., Vaissayre M. and Fournier D. (2005) Controlling an insecticide-resistant bollworm in West Africa. *Agriculture, Ecosystems & Environment* 107, 409–411.

Maxmen A. (2013) Crop pests: Under attack. *Nature* 501, S15–S17.

Mironidis G. K., Kapantaidaki D., Bentila M., Morou E., Savopoulou-Soultani M. and Vontas J. (2013) Resurgence of the cotton bollworm *Helicoverpa armigera* in northern Greece associated with insecticide resistance. *Insect Science* 20, 505–512.

Morandin L. A., Long R. F. and Kremen C. (2014) Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agriculture, Ecosystems & Environment* 189, 164–170.

Moreira C., Schiffers B. and Haubruge E. (2002) Caractérisation de la résistance au Sénégal d'*Helicoverpa armigera* Hübner (Lépidoptère, Noctuidae) par bioessai et méthodes moléculaires. *Parasitica* 58, 89–98.

Moustier P. (2007) Urban horticulture in Africa and Asia, an efficient corner food supplier. *Acta Horticulturae* 762, 145–148.

Netscher C. (1970) Les nématodes parasites des cultures maraîchères au Sénégal. *Cahiers ORSTOM, Série Biologie* 11, 209–229.

Neuenschwander P., Murphy S. T. and Coly E. V. (1987) Introduction of exotic parasitic wasps for the control of *Liriomyza trifolii* (Dipt., Agromyzidae) in Senegal. *Tropical Pest Management* 33, 290–297.

N'Guessan C. A., Abo K., Fondio L., Chiroleu F., Lebeau A., Poussier S., Wicker E. and Koné D. (2012) So near and yet so far: The specific case of *Ralstonia solanacearum* populations from Côte d'Ivoire in Africa. *Phytopathology* 102, 733–740.

Pfeiffer D. G., Muniappan R., Sall D., Diatta P., Diongue A. and Dieng E. O. (2013) First record of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Senegal. *Florida Entomologist* 96, 661–662.

Power A. G. (2010) Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 2959–2971.

Sam G. A., Osekre E. A., Mochiah M. B. and Kwoseh C. (2014) Evaluation of insecticides for the management of insect pests of tomato, *Solanum lycopersicon* L. *Journal of Biology, Agriculture and Healthcare* 4, 49–57.

Sigsgaard L., Greenstone M. H. and Duffield S. J. (2002) Egg cannibalism in *Helicoverpa armigera* on sorghum and pigeonpea. *BioControl* 47, 151–165.

Stroud J., Bush M. R., Ladd M. C., Nowicki R. J., Shantz A. A. and Sweatman J. (2015) Is a community still a community? Reviewing definitions of key terms in community ecology. *Ecology and Evolution* 5, 4757–4765.

Torres-Vila L. M., Rodriguez-Molina M. C. and Lacasa-Plasencia A. (2003) Testing IPM protocols for *Helicoverpa armigera* in processing tomato: Egg-count- vs. fruit-count-based damage thresholds using Bt or chemical insecticides. *Crop Protection* 22, 1045–1052.

Tropea Garzia G., Siscaro G., Biondi A. and Zappalà L. (2012) *Tuta absoluta*, a South American pest of tomato now in the EPPO region: Biology, distribution and damage. *EPPO Bulletin* 42, 205–210.

Umeh V. C., Kuku F. O., Nwanguma E. I., Adebayo O. S. and Manga A. A. (2002) A survey of the insect pests and farmers' practices in the cropping of tomato in Nigeria. *Tropicultura* 20, 181–186.

van Veenhuizen R. and Danso G. (2007) *Profitability and sustainability of urban and peri-urban agriculture*. Agricultural, Management, Marketing and Finance Occasional Paper, vol. 19. Food and Agriculture Organization of the United Nations, Rome, Italy. 95 pp.

Wyckhuys K., Bordat D., Desneux N. and Fuentes Quintero L. S. (2012) *Tuta absoluta* (Meyrick): Un ravageur invasif des cultures maraîchères pour l'Afrique sub-saharienne. In: *Nouveaux Ravageurs & Maladies Invasives, Guide 2. Comité de Liaison Europe-Afrique-Caraïbes-Pacifique*. Pesticide Initiative Programme (COLEACP-PIP), Brussels, Belgium.

Zappalà L., Biondi A., Alma A., Al-Jboory I. J., Arnò J., Bayram A., Chailleux A., El-Arnaouty A., Gerling D., Guenaoui Y., Shaltiel-Harpaz L., Siscaro G., Stavrinides M., Tavella L., Vercher Aznar R., Urbaneja A. and Desneux N. (2013) Natural enemies of the South American moth, *Tuta absoluta*, in Europe, North Africa and Middle East, and their potential use in pest control strategies. *Journal of Pest Science* 86, 635–647.