

# Dispersal of aphids, whiteflies and their natural enemies under photoselective nets

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**Abstract** Integrated Pest Management of insects includes several control tactics, such as the use of photoselective nets, which may reduce the flight activity of insects. Limiting the dispersal of pests such as aphids and whiteflies is important because of their major role as vectors of plant viruses, while a minor impact on natural enemies is desired. In this study, we examined for the first time the dispersal ability of three vector species, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), *Macrosiphum euphorbiae* (Thomas) (Hemiptera: Aphididae) and *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), in cages covered with photoselective nets. Contrary to the results obtained with aphids, the ability of the whitefly *B. tabaci*, to reach the target plant was reduced by photoselective nets. In a second set of experiments, the impact of UV-absorbing nets on the

visual cues of two important predator species, *Orius laevigatus* (Fieber) (Hemiptera: Anthocoridae) and *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae), was evaluated. The anthocorid was caught in higher numbers in traps placed under regular nets, whereas the mites preferably chose environments in which the UV radiation was attenuated. We have observed a wide range of effects that impedes generalization, although photoselective nets have a positive effect on pest management of whiteflies and aphids under protected environments.

**Keywords** Flight behaviour · *Macrosiphum euphorbiae* · *Myzus persicae* · *Bemisia tabaci* · *Orius laevigatus* · *Amblyseius swirskii*

## Introduction

Whiteflies and aphids are major pests to crops worldwide. They cause direct damage when they extract plant fluids and indirect damage by transmitting viral pathogens (Byrne and Bellows 1991; Foster et al. 2007). In this work, we have focused on three pest species of high agricultural importance: *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) and *Macrosiphum euphorbiae* (Thomas) (Hemiptera: Aphididae) and on two predators commonly released in protected crops for controlling *B.tabaci* and other key-pests: *Orius laevigatus* (Fieber) (Hemiptera: Anthocoridae)

and *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) (Bosco et al. 2008; Buitenhuis et al. 2010; Colomer et al. 2011).

The development of non-chemical methods for a successful integrated pest management (i.e. biological control or physical barriers) requires an understanding of the interactions between insects and their host plants as well as the ecology and behaviour of the pest species and their natural enemies (van Lenteren and Noldus 1990). In particular, a wide multidisciplinary knowledge is needed when studying the use of photoselective covers. This management tactic has arisen in the last 15 years and materials used in greenhouses mostly filter radiation in the ultraviolet (UV: 280–400 nm) range of the solar spectrum (Raviv and Antignus 2004). These film covers have been developed for use on several crops, targeting different pests (i.e. whiteflies, aphids, thrips and leafhoppers) that generally infest plants to a lower extent when UV is excluded from the environment (Chyzik et al. 2003; Diaz et al. 2006; Kumar and Poehling 2006; Doukas and Payne 2007a; Weintraub et al. 2008). Also, an alteration of visual behaviour has been reported for a few species inside structures covered with UV-absorbing films (Antignus et al. 2001; Mutwiwa et al. 2005; Doukas and Payne 2007b; Weintraub et al. 2008). On the other hand, reports on the behaviour of beneficial insects on crops protected with UV-absorbing covers indicate species-specific responses in parasitoids (Chyzik et al. 2003; Chiel et al. 2006; Sal et al. 2009), but similar studies have not yet been made for predators.

Ultraviolet radiation is a key component in photo-reception of insects and vision is likely to modulate their flight and dispersal behaviour. Mound (1962) first described two ranges of the spectrum, yellow and blue/ultraviolet, to which *B. tabaci* is particularly sensitive. In the case of aphids, the only species in which spectral sensitivity has been studied is *M. persicae*. This species showed a maximum response at green (530 nm), a secondary blue-green peak (440–480 nm) and a third peak in the near UV (330–340 nm) (Kirchner et al. 2005).

However, little attention has been given to the visual capacities of insects that belong to the predatory guild and no spectral sensitivity data are available for anthocorids. Although not much is known about the dispersal of natural enemies throughout a crop, it is a key component of successful biological control

(Buitenhuis et al. 2010). Some studies have focused on the attraction of *Orius* spp. by volatile compounds from prey and visual learning (Henaut et al. 1999; Mochizuki and Yano 2007). Moreover, interplant dispersal of the phytoseiid mite *A. swirskii* is considered to be limited in space and it is mostly observed between plants with canopies in contact with each other (Buitenhuis et al. 2010).

Although several authors have already reported the efficacy of UV-absorbing nets or screens in reducing natural pest infestations (Legarrea et al. 2010, and references therein), there is a lack of information on the dispersal of pests and natural enemies inside nethouses. Because nets are currently used to protect tropical, subtropical and Mediterranean crops from pest damage (Weintraub 2007; Castilla and Montero 2008), further knowledge is needed to understand the processes that occur underneath UV-absorbing screens. The objective of this work was to evaluate the effects of photoselective nets on the dispersal of key pests of protected crops (the whitefly *B. tabaci*, and the aphids *M. persicae* and *M. euphorbiae*) and two of the main natural enemies of *B. tabaci* (*O. laevigatus* and *A. swirskii*).

## Materials and methods

The experiments were carried out at two sites: the Institute for Agronomic Sciences, ICA-CSIC (Madrid, Spain) and the Gilat Research Center, ARO (Negev, Israel). The nets studied had different photoselective properties and their physical and optical properties, are summarised in Table 1 and Fig. 1. Experiments involving the dispersal of aphids and whiteflies were conducted in greenhouse facilities, while the experimental display for the predator study was located outdoors. Environmental conditions were monitored regularly at the experimental sites (Table 2). A particular experiment was designed for each specific guild, as described below.

### Insect cultures and plants

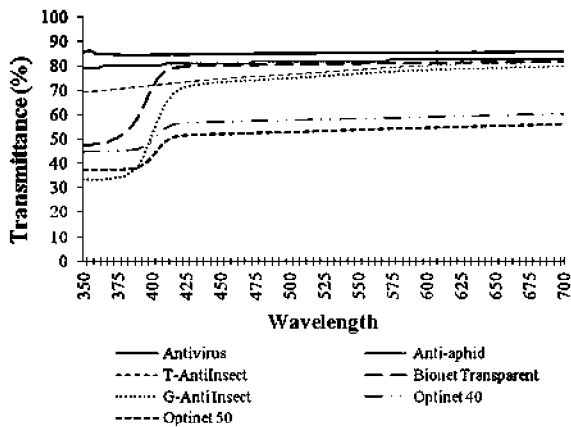
Whiteflies (*B. tabaci* biotype Q) were reared on melon plants (*Cucumis melo* L. 'Primal') in insect-proof cages located in the greenhouse facilities at an average temperature (L:D) of 24:20°C and 60:70% of RH. The aphid colonies were reared in an insectary with

**Table 1** Description of the nets used in the experiments

Type of net <sup>a</sup>	PAR (400–700 nm) transmittance (%)	UV (320–700 nm) transmittance (%)	Mesh <sup>b</sup>	Manufacturer
P-Optinet 50	54	38	50	1
P-Optinet 40	58	46	40	1
G-Anti Insect	76	37	50	1
Bionet Transparent	80	54	50	2
T-Anti Insect	78	70	50	1
Anti-aphid net	82	80	50	3
Antivirus net	85	85	50	2

<sup>a</sup> Three companies supplied nets for the studies: (1) Polysack Plastic Industries Ltd. (Nir Yitzhak, Israel); (2) Meteor Agricultural Nets Ltd. (Petach-Tikva, Israel), (3) Criado y López S.L. (El Ejido, Spain)

<sup>b</sup> Mesh: Number of threads per inch in the tightest direction of the woven net



**Fig. 1** Percentage of radiation transmitted for each net in solar spectrum from 350 to 700 nm, measured by a UV–VIS spectroradiometer using an integrating sphere

controlled conditions (L:D): photoperiod 16:8, temperature 23:18°C, and RH 60:80%. The colony of *M. euphorbiae* was collected in a lettuce crop in Villa del Prado (Madrid, Spain) in 1999 and reared for the experiments on *Lactuca sativa* L. cv longifolia ‘Moratina’ (Syngenta Seeds, Barcelona, Spain). In the same way, the colony of *M. persicae* was initiated from a female collected in a pepper crop located in El Encín (Madrid, Spain) in 1989 and reared on *Brassica rapa* L. ‘Just Right’ (Taki Europe BV, De Kwakel, The Netherlands). Additionally, predators were provided by Biobee Biological Systems (Sde Eliyahu, Israel) and kept for the experimental time in optimum conditions. Free access to water and corn pollen was given to the colony of *A. swirskii* following the methodology established by Weintraub et al. (2006).

*Orius laevigatus* was kept in cages together with green beans, soaked cotton, eggs of *Ephestia kuehniella* Zeller, corn pollen and buckwheat husks. Four different plant species [lettuce (*L. sativa* cv longifolia ‘Moratina’), turnip (*B. rapa* ‘Just Right’), tomato (*Solanum lycopersicum* L. ‘Marmande’) and pepper (*Capsicum annuum* L. ‘Miko’)] were used as targets in the experiments depending on the arthropod tested.

#### No choice chamber units

To evaluate aphid and whitefly dispersal under radiation modified environments, one-chamber cages (1 m long × 0.6 m wide × 0.6 m height) were used. Two cages were covered with each of the nets studied: P-Optinet 40, P-Optinet 50 and a standard (Anti-aphid) net with no photoselective properties (Fig. 1; Tables 1, 2). As shown in Table 1, the photoselective nets (P-Optinet) drastically reduced transmittance of the ultraviolet radiation up to 38–46%. Also, a partial blockage of photosynthetically active radiation (PAR: 400–700 nm) was observed in photoselective nets, that transmitted 54–58% of incident PAR radiation compared to the 80% transmitted through the standard net. The target plant was located at one end of the cage and impregnated with sticky glue (Tanglefoot, The Tanglefoot Company, MI, USA) to trap any insects landing on the plant and prevent insects moving back to the release area. At the opposite end of the chamber, a release platform was hung from the ceiling at a height of 40 cm to release insects, as described in Fereres et al. (1999) (Fig. 2a). In the aphid trials, a glass Petri dish (8 cm in diameter) in the platform was

**Table 2** Environmental conditions during the experiments (Mean  $\pm$  SE)

Experiment	Temperature day/night ( $^{\circ}$ C)	HR (%)	PAR outside ( $\mu$ mol $m^{-2} s^{-1}$ )	PAR in greenhouse <sup>c</sup> ( $\mu$ mol $m^{-2} s^{-1}$ )	UVR in greenhouse <sup>c</sup> ( $\mu$ mol $m^{-2} s^{-1}$ )	Anti-aphid net <sup>c</sup> (PAR/UVR) ( $\mu$ mol $m^{-2} s^{-1}$ )	P-Optinet 40 <sup>c</sup> (PAR/UVR) ( $\mu$ mol $m^{-2} s^{-1}$ )	P-Optinet 50 <sup>c</sup> (PAR/UVR) ( $\mu$ mol $m^{-2} s^{-1}$ )
<i>B. tabaci</i> <sup>a</sup>	23:18	61 $\pm$ 2	1,743	344 $\pm$ 18	17 $\pm$ 1	154/7.0	124/3.8	99/3.0
<i>M. persicae</i> <sup>a</sup>	25:21	70 $\pm$ 2	2,135	275 $\pm$ 19	12 $\pm$ 1	181/7.8	117/3.7	118/3.2
<i>M. euphorbiae</i> <sup>a</sup>	26:21	76 $\pm$ 1	1,264	343 $\pm$ 15	16 $\pm$ 1	132/5.3	96/2.9	78/2.4
<i>O. laevigatus</i> <sup>b</sup>	26:-	51 $\pm$ 8	1,725	-	-	-	-	-
<i>A. swirskii</i> <sup>b</sup>	23:-	64 $\pm$ 3	1,304	-	-	-	-	-

<sup>a</sup> Experiments set-up at the ICA greenhouse facilities (Madrid, Spain)

<sup>b</sup> Experiments conducted in outside conditions at Gilat Research Station (Negev, Israel)

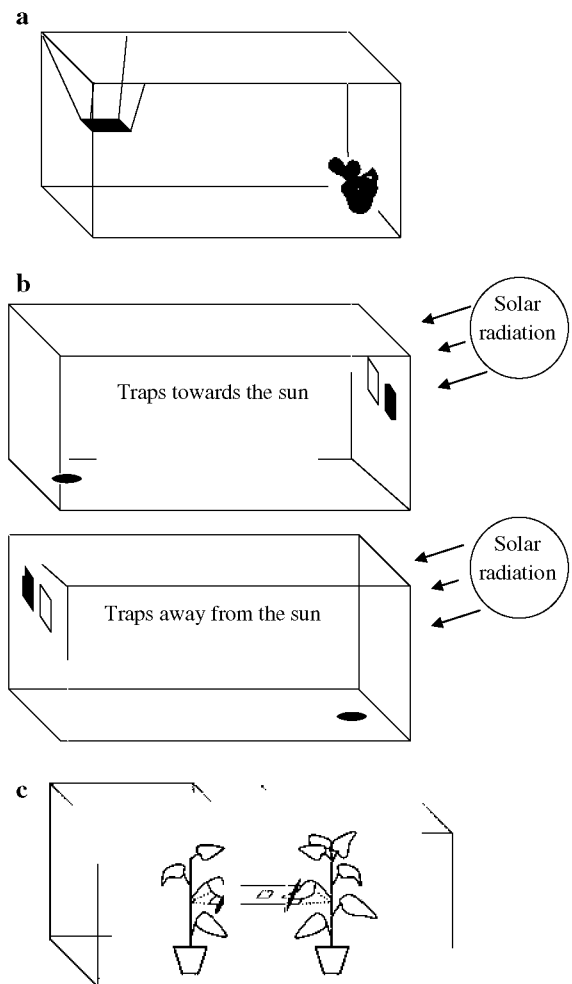
<sup>c</sup> Average radiation measured at midday (solar time), using quantum meters sensitive to PAR (400–700 nm) and UVR (320–400 nm) (BQM and UVM, Apogee, Logan, UT, USA)

substituted for glass tubes to facilitate the take-off of insects. The experiment was repeated five times for *B. tabaci* and six times for *M. euphorbiae* and *M. persicae*. With every repetition, cage position was rotated to avoid a bias due to spatial environmental variation inside the greenhouse. Two hundred whiteflies and one hundred aphids were released into each cage, and the number of insects trapped on the plant was monitored periodically at different time intervals (at 2, 4, 6, 8, 24 h for aphids and at 2, 8, 24 h for whiteflies).

In the experiments that evaluated the dispersal of *O. laevigatus*, a set of six cages ( $1.20 \times 0.6 \times 0.6$  m) was used. Three cages were covered with T-Anti Insect net (as a standard non-UV absorbing net) and the remaining three cages were covered with G-Anti Insect net, which transmitted only 37% of incident UV radiation while allowing the passage through the net of 76% of PAR (Fig. 1; Table 1). Two sticky traps ( $10 \times 14$  cm), one yellow and the other white were used as stimuli to attract the insects. Twenty-five *O. laevigatus* (adults) were released one meter away from the sticky traps on a Petri dish (8 cm diameter) laying on the floor of the cage, and the number of insects trapped was checked 4 h later (Fig. 2b). The experiment was repeated six times, and two–three replicates of each net were simultaneously used. Cages were rotated as sun progressed to prevent shadows inside the chamber. Also, the position of the traps in the cages (either towards the sun or away from it) was changed at every repetition (Fig. 2b).

#### Choice chamber units

To evaluate the choice-behaviour of *A. swirskii* regarding UV-deficient *versus* UV-standard environments a choice chamber unit was designed. Two cages ( $50 \times 50 \times 50$  cm) with frames built from wooden sticks (2 cm wide) were joined by a narrow black plastic cylinder (16 cm in diameter). One cage was covered with a UV-absorbing net (Bionet transparent) that only transmitted 54% of UV radiation, whereas the other was covered with a non-UV absorbing net (Antivirus net) (Fig. 1; Table 1). For the experiment, one pepper plant (7–9 leaves and 18–22 cm high) was placed in each cage. The plants were joined by a cardboard platform ( $15 \times 3$  cm) attached to each stem with a metal wire. One pepper leaf from each plant was held to the platform with a clip, apices being separated



**Fig. 2** Schematics of the different experimental set-ups. **a** Chamber unit used in the non-choice experiments with aphids and whiteflies. The wooden frame, except for the floor, was covered with a UV-absorbing net. The floor was a white wooden board. Insects were released from a hanging platform and a host plant was placed as a target. **b** The chamber unit used in experiments with *O. laevigatus* was similar to the one described in (a), but the release area was located on the floor, which was a layer of UV-absorbing net and two sticky traps were used as appropriate targets. The set-up was placed either towards or away the incident solar radiation. **c** Choice chamber units to study the dispersal of *A. swirskii*. Two wooden cages were connected by a black cylinder, and a bridge was created by a cardboard platform attached with metal wires to each of the plants placed in the cages. The release area was  $1 \text{ cm}^2$  and delimited in the central area of the platform

5 cm. One square centimetre was delimited in the middle of the platform as the mite release area (Fig. 2c). In each trial, five to eight hundred mites were released in the central square of the platform.

Two hours later, in order to trap mites that moved from the platform to each environment the aerial parts of the pepper plants were washed into containers partially filled with 80% ethanol. In the laboratory, the contents of the jars were observed under a stereoscopic microscope, counting all mites present in the sample. Thus, the proportion of mites under each cover was calculated.

### Statistical analysis

In non-choice experiments, the accumulated percentage of insects found on the target in the cages covered with each of the nets tested was compared in every period of time using one-way ANOVA ( $P = 0.05$ ) followed by pairwise comparisons for least significant differences (LSD). To achieve normality, the data were arcsin-square-root transformed:  $y = 2 \times \arcsin \sqrt{x}$ , where  $x$  is the proportion of insects captured. Then, in case the transformed data were still not normally distributed ( $P < 0.05$  in the Kolmogorov–Smirnov test of normality), a non-parametric Mann–Whitney  $U$  test ( $P = 0.05$ ) was applied to compare results between the types of nets. In choice experiments, a  $\chi^2$  goodness of fit test ( $P = 0.05$ ) was performed to compare the proportion of insects that was found under each net. The data were analysed with the SPSS 17.0 statistical package SPSS (Inc 2009).

## Results

### Dispersal of whiteflies and aphids

As shown in Table 3, a lower percentage of *B. tabaci* landed on the target plants under the photoselective nets (P-Optinet 50 and P-Optinet 40) compared to that

**Table 3** Cumulative percentage of the total released *B. tabaci* that landed on the target tomato plants at different periods of time (mean  $\pm$  SE) ( $n = 10$ )

Type of net	2 h	8 h	24 h
P-Optinet 50	9.9 $\pm$ 1.3 a	30.0 $\pm$ 1.6 a	31.8 $\pm$ 1.6 a
P-Optinet 40	11.5 $\pm$ 0.9 a	31.9 $\pm$ 1.3 a	33.6 $\pm$ 1.6 a
Anti-aphid	17.2 $\pm$ 0.9 b	41.6 $\pm$ 1.4 b	43.8 $\pm$ 1.5 b

Different letters in columns indicate statistically significant differences among the types of nets by ANOVA and LSD ( $P = 0.05$ )

under the Standard control net with no UV-absorbing properties (Anti-aphid net). The differences were statistically significant from the very beginning of the experiment, 2 h after release ( $F = 9.23$ ;  $df = 2, 27$ ;  $P = 0.001$ ) and remained the same 8 h ( $F = 16.21$ ;  $df = 2, 27$ ;  $P < 0.001$ ) and 24 h later ( $F = 15.40$ ;  $df = 2, 27$ ;  $P < 0.001$ ).

In all cases, no significant differences were found in the number of whiteflies caught under the two different types of photoselective nets (Table 3). About  $35.2 \pm 1.8\%$  (mean  $\pm$  SE) of the whiteflies that landed on the plant did so during the first 2 h of the experiment, whereas only  $5.2 \pm 0.8\%$  landed later than 8 h after insect release. However, opposite results were obtained with both aphid species tested (Tables 4, 5). The results of the *M. euphorbiae* dispersal experiments (Table 4) show that more insects landed on the plants in cages covered with P-Optinet nets during most of the time periods studied: 4 h ( $F = 4.81$ ;  $df = 2, 33$ ;  $P = 0.015$ ), 6 h ( $F = 6.02$ ;  $df = 2, 33$ ;  $P = 0.006$ ), 8 h ( $F = 5.30$ ;  $df = 2, 33$ ;  $P = 0.01$ ) and 24 h ( $F = 4.18$ ;  $df = 2, 33$ ;  $P = 0.024$ ), although no significant differences were found 2 h after release ( $F = 3.10$ ;  $df = 2, 33$ ;  $P = 0.06$ ). In contrast to whiteflies, only  $12.1 \pm 1.4\%$  of the total recaptured aphids reached the plant in 2 h. In this case, a longer experimental period (6 h) was necessary to find  $37.4 \pm 2.8\%$  of the *M. euphorbiae* recaptured adults trapped on the target plant. Similar results were also observed in the *M. persicae* experiment, where only  $6.5 \pm 2.1\%$  of the total captured aphids reached the plant in 2 h. Moreover, the experiment was left running for 6 h until  $43.3 \pm 3.3\%$  of the captured insects had landed on the target plant. Six hours after release, the percentage of *M. persicae* landing on the plant was significantly higher under the UV-absorbing nets than under the control nets ( $F = 3.53$ ;  $df = 2, 33$ ;  $P = 0.041$ ), the same as observed for *M. euphorbiae*. Although no statistically significant differences were found during other periods, there was a trend showing higher numbers of aphids trapped under both UV-absorbing covers (P-Optinet 50 and P-Optinet 40) than under the non-UV absorbing control net (Anti-aphid net).

### Dispersal of predators

A low number of *O. laevigatus* individuals were found in the sticky traps (1–15%) and the variable was not

**Table 4** Cumulative percentage of the total released *M. euphorbiae* that landed on the target lettuce plant at different periods of time (mean  $\pm$  SE) ( $n = 12$ )

Type of net	2 h	4 h	6 h	8 h	24 h
P-Optinet 50	6.1 $\pm$ 1.1 a	17.4 $\pm$ 3.0 b	34.4 $\pm$ 3.5 b	43.7 $\pm$ 4.7 b	46.1 $\pm$ 4.9 b
P-Optinet 40	7.7 $\pm$ 2.2 a	16.9 $\pm$ 3.0 b	30.8 $\pm$ 4.1 b	42.6 $\pm$ 7.0 b	48.0 $\pm$ 7.4 b
Anti-aphid	2.7 $\pm$ 0.8 a	8.2 $\pm$ 1.5 a	18.5 $\pm$ 3.1 a	23.9 $\pm$ 3.9 a	27.2 $\pm$ 4.4 a

Different letters in columns indicate statistically significant differences among the types of nets by ANOVA and LSD ( $P = 0.05$ )

**Table 5** Cumulative percentage of the total released *M. persicae* that landed on the target turnip plant at different periods of time (mean  $\pm$  SE) ( $n = 12$ )

Type of net	2 h	4 h	6 h	8 h	24 h
P-Optinet 50	5.5 $\pm$ 3.0 a	24.6 $\pm$ 4.6 a	49.7 $\pm$ 4.6 b	55.3 $\pm$ 4.5 a	57.1 $\pm$ 4.3 a
P-Optinet 40	4.3 $\pm$ 2.4 a	18.2 $\pm$ 5.0 a	41.6 $\pm$ 5.5 ab	48.8 $\pm$ 5.5 a	52.3 $\pm$ 5.3 a
Anti-aphid	2.4 $\pm$ 1.6 a	11.7 $\pm$ 2.8 a	32.2 $\pm$ 3.6 a	41.0 $\pm$ 3.1 a	45.5 $\pm$ 2.4 a

Different letters in columns indicate statistically significant differences among the types of nets when ANOVA and LSD ( $P = 0.05$ )

normally distributed. Thus, non-parametric statistics were necessary. The number of captures was split into four groups: yellow traps, white traps, cages oriented towards the sun and cages oriented away from the sun. In each group, the two types of nets were compared. Data are indicative of a lack of effect of the type of net on insect captures when the traps were oriented towards the sun for both the yellow ( $U = 40.5$ ,  $df = 1$ ,  $P = 1.00$ ) and the white traps ( $U = 40.0$ ,  $df = 1$ ,  $P = 0.96$ ). In contrast, when traps were oriented away from the sun, data suggest that the percentage of insects captured was higher under the non-photosensitive net (T-Anti Insect) for both colours of trap (yellow:  $U = 14.0$ ,  $df = 1$ ,  $P = 0.04$  and white:  $U = 9.0$ ,  $df = 1$ ,  $P = 0.01$ ) (Table 6).

Finally, when the distribution of *A. swirskii* between both environments was tested, significant differences were scored ( $\chi^2 = 21.444$ ,  $df = 1$ ,  $P < 0.001$ )

**Table 6** Percentage of the total released *O. laevigatus* adults captured in sticky traps (mean  $\pm$  SE) ( $n = 9$ )

Position	Colour	T-anti insect	G-anti insect
Towards the sun	Yellow	2.7 $\pm$ 1.2 a	2.7 $\pm$ 1.2 a
	White	9.3 $\pm$ 3.0 a	9.3 $\pm$ 2.5 a
Away from the sun	Yellow	4.5 $\pm$ 1.4 b	1.0 $\pm$ 0.7 a
	White	15.0 $\pm$ 1.8 b	6.0 $\pm$ 2.4 a

Different letters in rows indicate statistically significant differences among the types of net by the Mann-Whitney  $U$  test ( $P = 0.05$ )

concerning the percentage of *A. swirskii* preferring the UV-absorbing net (Bionet transparent) ( $57.94 \pm 0.22\%$ ) compared to the standard (Antivirus net) ( $45.96 \pm 0.24\%$ ), although values were in both cases close to 50%.

## Discussion

Different kinds of experimental set ups based on cages covered with photosensitive films have been tested to analyze their influence on insect dispersal towards host plants or coloured targets (Costa and Robb 1999; Doukas and Payne 2007b, c; Weintraub et al. 2008). In such experiments, insects are released into the structure, allowed to fly freely and their ability to find a target is later evaluated. Even though photosensitive nets (P-Optinet, Bionet), are currently available in the horticultural industry (Ben-Yakir et al. 2008) and have been tested in field conditions (Antignus et al. 1998; Kumar and Poehling 2006; Legarrea et al. 2010), experiments to study insect orientation towards a host plant have not been performed yet. Antignus et al. (2001) studied flight behaviour of whiteflies under UV-absorbing plastic films, but our study reports for the first time the effect of photosensitive nets on aphid orientation towards target plants at short distances.

As previously reported by several authors who studied the effect of UV-absorbing plastic films on whitefly dispersal (Mutwiwa et al. 2005; Doukas and

Payne 2007b), a lower percentage of the released *B. tabaci* were found in the target plants inside cages covered with photosensitive materials. Thus, even though nets and screens are not continuous layers of material and they allow the passage of unfiltered radiation, P-Optinet covers reduced approximately 42–52% of UV and 30–34% of PAR transmittance compared to a standard net. Such modification was enough to alter the usual behaviour of whiteflies reducing both flight activity and dispersal (Raviv and Antignus 2004). As previously reported, a positive correlation has been established between the amount of UV filtration and the level of protection against insects (Antignus 2000). It is also reported that lower light intensities may also contribute to reduce flight activity of whiteflies (Doukas and Payne, 2007b). The use of P-Optinet 40-mesh nets seemed to provide similar results as the P-Optinet 50-mesh nets, so the benefit of slightly increased ventilation in 40-mesh screens makes this type of net a good alternative for protecting crops against *B. tabaci*.

On the other hand, rather unexpected results were obtained for the dispersal of aphids: a higher percentage landed on the host plants in cages covered with photosensitive nets than in those covered with standard nets. In the case of aphids, only field experiments have been conducted using UV-absorbing materials, where a lower natural infestation of aphids was observed (Chyzik et al. 2003; Diaz et al. 2006; Kumar and Poehling 2006).

Vision in both whiteflies and aphids may be altered by UV-absorbing covers in the same way. Takeoff and flight activities are enhanced in the presence of shortwave radiation (blue/ultraviolet) whereas reflected or transmitted yellow/green radiation induces alighting behaviour and favours settling (Kring 1972; Vaishampayan et al. 1975; Coombe 1982). Thus, flight activity may be altered and takeoff could be reduced underneath UV-cladding materials. Although both insects may share similar peaks of spectral sensitivity in UV and green spectrum, the particular physiological flight “mood” may result in rather striking differences among species. In contrast to whiteflies that showed an active host-seeking behaviour starting earlier than 2 h after the release, aphids kept on flying for a longer time in a migratory “mood”. In particular, aphid flight pattern showed a strong attraction towards sunlight 2–6 h after release and a low response to target plants, which is consistent

with what was reported by Kring (1972). Later on, the aphids turned to host-seeking mode and landed on the target plants. The greater reduction of UV transmittance under P-Optinet may have increased the green stimuli from the plant surface which resulted in a higher attraction and landing rate of aphids. In line with this flight behaviour, aphids that would be feeding on a host plant under UV-absorbing covers may have a reduced stimulus for take-off and would remain longer on their host plants. Eventually, this altered behaviour may reduce the spread of non-persistent aphid-transmitted viruses as it has been reported for lettuce viruses in field trials (Diaz et al. 2006), but further experiments should be conducted to confirm these findings.

We have obtained a low number of *O. laevigatus* captured in colour traps. However, significant differences that occurred among the treatments showed that visual cues in *O. laevigatus* may be disturbed under UV-absorbing covers, inducing a reduction in dispersal. A lower percentage of insects were trapped in cages whose sticky traps were located on the opposite direction of the solar radiation stimuli. In the reverse experimental set-up, the role of solar radiation as a positive stimulus may have induced the insects to disperse towards the traps, resulting in no differences between types of covers. Moreover, our data suggest a higher percentage of insects captured in white traps than yellow ones, as was recently also reported for the closely related anthocorid species *Orius niger* Wolff (Atakan and Bayram 2011). It still remains to be determined whether this species uses other senses to find its host and maintain its efficacy as biological control agent under UV-absorbing covers. From our point of view, visual and chemical cues involved in anthocorid dispersal is an unexplored field that deserves further research.

Our results suggest that UV-deficient environments induced under photosensitive screens might be attractive for *A. swirskii*. It is possible that the predatory mite attempts to avoid UV-B radiation that may cause severe injuries reducing survival, egg laying and hatching, as has been found for other predatory mite species (Onzo et al. 2010). Previous studies have shown that mites belonging to both: phytophagous and predatory guilds tend to be located in refuges where UV-B radiation is reduced, such as the underside of leaves (Ohtsuka and Osakabe 2009; Onzo et al. 2010) or in plant apices (Onzo et al. 2010). Although the



attenuation of UV radiation may create an attractive environment for *A. swirskii*, an alteration in the host-seeking behaviour of the predatory mite would not be expected. Phytoseiids mainly exploit plant volatiles to locate prey patches (Margolies et al. 1997) and they do not have proper eyes or visual sensory structures.

Different effects were obtained for both predator species showing that any generalisation about the effect of UV-absorbing covers on arthropods may lead to inadequate interpretations. The same situation was observed when analysing the effects of UV-absorbing covers on different Hymenoptera parasitoids. Only those species that show a typical host-seeking behaviour and rely on their vision to find a host to parasitize (i.e. *Eretmocerus mundus* Mercet) suffer similar difficulties as several pests when greenhouse covers filter UV radiation (Chiel et al. 2006). Knowing the degree of compatibility between each biological control and the use of UV-absorbing covers is crucial for successful pest management in protected crops. In cases where the dispersal of natural enemies was adversely affected by the lack of UV radiation (i.e. *O. laevigatus* and *E. mundus*), several strategies, such as releasing the insects at several points within the greenhouse, may be used for successful control (Chiel et al. 2006).

To summarize, an altered host-seeking behaviour has been observed for whiteflies and aphids suggesting that the use of photoselective nets is a good strategy to be used in IPM. However, further studies on the particular effect of the lack of UV radiation on each particular pest and biological control agent system should be performed because generalisations in this context may lead to incorrect conclusions.

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## References

- Antignus Y (2000) Manipulation of wavelength dependent behavior of insects: an IPM tool to impede insects and restrict epidemics of insect-borne viruses. *Virus Res* 71:213–220
- Antignus Y, Lapidot M, Hadar D, Messika Y, Cohen S (1998) Ultraviolet-absorbing screens serve as optical barriers to protect crops from virus and insect pests. *J Econ Entomol* 91:1401–1405
- Antignus Y, Nestel D, Cohen S, Lapidot M (2001) Ultraviolet-deficient greenhouse environment affects attraction and flight behaviour. *Environ Entomol* 30:394–399
- Atakan E, Bayram A (2011) Distributions of western flower thrips (Thysanoptera: Thripidae) and its predatory bug *Orius niger* (Hemiptera: Anthocoridae) assessed by coloured sticky traps and plant samplings in cotton. *Arch Phytopathol Plant Prot* 44:1595–1608
- Ben-Yakir D, Hadar MD, Offir Y, Chen M, Tregerman M (2008) Protecting crops from pests using OptiNet<sup>®</sup> and Chroma-tiNet<sup>®</sup> shading nets. *Acta Hort* 770:205–212
- Bosco L, Giacometto E, Tavella L (2008) Colonization and predation of thrips (Thysanoptera: Thripidae) by *Orius* spp. (Heteroptera: Anthocoridae) in sweet pepper greenhouses in northwest Italy. *Biol Control* 44:331–340
- Buitenhuis R, Shipp L, Scott-Dupree C (2010) Dispersal of *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) on potted greenhouse chrysanthemum. *Biol Control* 52:110–114
- Byrne DN, Bellows TS (1991) Whitefly biology. *Annu Rev Entomol* 36:431–457
- Castilla N, Montero JI (2008) Environmental control and crop production in Mediterranean greenhouses. *Acta Hort* 797:25–36
- Chiel E, Messika Y, Steinberg S, Antignus Y (2006) The effect of UV-absorbing plastic sheet on the attraction and host location ability of three parasitoids: *Aphidius colemani*, *Diglyphus isaea* and *Eretmocerus mundus*. *BioControl* 51:65–78
- Chyzik R, Dobrinin S, Antignus Y (2003) Effect of a UV-deficient environment on the biology and flight activity of *Myzus persicae* and its hymenopterous parasite *Aphidius matricariae*. *Phytoparasitica* 31:467–477
- Colomer I, Aguado P, Medina P, Heredia RM, Fereres A, Belda JE, Viñuela E (2011) Field trial measuring the compatibility of methoxyfenozide and flonicamid with *Orius laevigatus* Fieber (Hemiptera: Anthocoridae) and *Amblyseius swirskii* (Athias-Henriot) (Acari: Phytoseiidae) in a commercial pepper greenhouse. *Pest Manag Sci* 67:1237–1244
- Coombe PE (1982) Visual behaviour of the greenhouse whitefly, *Trialeurodes vaporariorum*. *Physiol Entomol* 7: 243–251
- Costa HS, Robb KL (1999) Effects of ultraviolet-absorbing plastic films on flight behaviour of *Bemisia argentifolii* (Homoptera: Aleyrodidae) and *Frankliniella occidentalis* (Thysanoptera: Thripidae). *J Econ Entomol* 92:557–562
- Diaz BM, Biurrún R, Moreno A, Nebreda M, Fereres A (2006) Impact of ultraviolet-blocking plastic films on insect vectors of virus diseases infesting crisp lettuce. *Hortscience* 41:711–716
- Doukas D, Payne CC (2007a) The use of ultraviolet-blocking films in insect pest management in the UK, effects on naturally occurring arthropod pest and natural enemy populations in a protected cucumber crop. *Ann Appl Biol* 151:221–231

- Doukas D, Payne CC (2007b) Greenhouse whitefly (Homoptera: Aleyrodidae) dispersal under different UV-light environments. *J Econ Entomol* 100:389–397
- Doukas D, Payne CC (2007c) Effects of UV-blocking films on the dispersal behaviour of *Encarsia formosa* (Hymenoptera: Aphelinidae). *J Econ Entomol* 100:110
- Fereres A, Kampmeier GE, Irwin ME (1999) Aphid attraction and preference for soybean and pepper plants infected with Potyviridae. *Ann Entomol Soc Am* 92:542–548
- Foster SP, Devine G, Devonshire AL (2007) Insecticide resistance. In: van Emden HF, Harrington R (eds) *Aphids as crop pests*. CABI, Wallingford, UK, pp 261–285
- Henaut Y, Alauzet C, Dargagnon D, Lambin M (1999) Visual learning in larval *Orius majusculus* a polyphagous predator. *Entomol Exp Appl* 90:103–107
- Kirchner SM, Döring TF, Saucke H (2005) Evidence for trichromacy in the green peach aphid, *Myzus persicae* (Sulz.) (Hemiptera: Aphididae). *J Insect Physiol* 51:1255–1260
- Kring JB (1972) Flight behaviour of aphids. *Annu Rev Entomol* 17:461–492
- Kumar P, Poehling HM (2006) UV-blocking plastic films and nets influence vectors and virus transmission on greenhouse tomatoes in the humid tropics. *Environ Entomol* 35:1069–1082
- Legarrea S, Karnieli A, Fereres A, Weintraub PG (2010) Comparison of UV-absorbing nets in pepper crops: spectral properties, effects on plants and pest control. *Photochem Photobiol* 86:324–330
- Margolies DC, Sabelis MW, Boyer JE (1997) Response of a phytoseiid predator to herbivore-induced plant volatiles: selection on attraction and effect on prey exploitation. *J Insect Behav* 10:695–709
- Mochizuki M, Yano E (2007) Olfactory response of the anthorid predatory bug *Orius sauteri* to thrips-infested egg-plants. *Ent Exp Appl* 123:57–62
- Mound LA (1962) Studies on the olfaction and colour sensitivity of *Bemisia tabaci* (Genn.) (Homoptera, Aleyrodidae). *Ent Exp Appl* 5:99–104
- Mutwiwa UN, Borgemeister C, Von Elsner B, Tanau HJ (2005) Effects of UV-absorbing plastic films on greenhouse whitefly (Homoptera: Aleyrodidae). *J Econ Entomol* 98:1221–1228
- Ohtsuka K, Osakabe MMH (2009) Deleterious effects of UV-B radiation on herbivorous spider mites: they can avoid it by remaining on lower leaf surfaces. *Environ Entomol* 38:920–929
- Onzo A, Sabelis MW, Hanna R (2010) Effects of ultraviolet radiation on predatory mites and the role of refuges in plant structures. *Environ Entomol* 39:695–701
- Raviv M, Antignus Y (2004) UV radiation effects on pathogens and insect pest of greenhouse-grown crops. *Photochem Photobiol* 79:219–226
- Sal J, Velázquez E, Legarrea S, Aguado P, Fereres A, Morales I, del Estal P, Viñuela E (2009) Influence of UV-absorbing nets in the population of *Macrosiphum euphorbiae* Thomas and the parasitoid *Aphidius ervi* (Haliday) in lettuce crops. In: *Proceedings of the third international symposium Biological Control Arthropods*, Christ Church, New Zealand, 8–13 Feb, 2009, pp 329–337
- SPSS Inc (2009) SPSS statistical package, 17.0 version, Chicago, SPSS Inc
- Vaishampayan SM, Kogan M, Waldbauer GP, Woolley JT (1975) Spectral specific responses in the visual behaviour of the greenhouse whitefly, *Trialeurodes vaporariorum* (Homoptera: Aleyrodidae). *Ent Exp Appl* 18:344–356
- van Lenteren JC, Noldus JJ (1990) Whitefly-plant relationships: behavioural and ecological aspects. In: Gerling D (ed) *Whiteflies: their bionomics, pest status and management*. Intercept Ltd, Hants, UK, pp 47–89
- Weintraub PG (2007) Integrated control of pests in tropical and subtropical sweet pepper production. *Pest Manag Sci* 63:753–760
- Weintraub PG, Kleitman S, Shapira N, Argov Y, Palevsky E (2006) Efficacy of *Phytoseiulus persimilis* versus *Neoseiulus californicus* for controlling spider mites on greenhouse sweet pepper. *IOBC/WPRS Bull* 29:121–125
- Weintraub PG, Pivonia S, Gera A (2008) Physical control of leafhoppers. *J Econ Entomol* 101:1337–1340

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