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Phototactic response of *Frankliniella occidentalis* to sticky traps with blue light emitting diodes in herb and *Alstroemeria* greenhouses

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Abstract

Blue and yellow sticky traps equipped with blue light emitting diodes (LEDs) were evaluated for their attractiveness to the western flower thrips (*Frankliniella occidentalis* Pergande) and compared to similar traps without light in two greenhouses with commercial production of either mixed herbs or *Alstroemeria* cut flowers. Blue traps were more attractive to *F. occidentalis* than the yellow traps in both crops, regardless of whether they were equipped with light or not. In herbs, the blue light equipped traps caught 1.7 to 2.5 times more thrips compared to blue traps without light, and 1.7 to 3.0 times more thrips than yellow traps with light. Blue light on both blue and yellow traps increased thrips catches in one out of two experiments in *Alstroemeria*. The blue light equipped traps caught 3.4 and 4.0 times more thrips than blue traps without light in coloured and white *Alstroemeria* cultivars, respectively, whereas yellow light equipped traps increased thrips catches 4.5 times compared to yellow traps without light in both coloured and white cultivars. The yellow light equipped traps caught, however, only equal to or only slightlymore thrips than blue traps without light, and caught fewer thrips than the light equipped blue traps. The relative trapping efficiency of the different combinations of trap colour and light varied with experiment, crop and *Alstroemeria* cultivars. This suggests that factors other than merely the addition of light influenced the thrips' phototactic response to the traps. Such factors could be differences in the relative strength of the competition between attractive signals from traps and plants between the two crops and *Alstroemeria* cultivars, thrips density, seasonal lighting conditions or different pest management strategies and other operational procedures in the greenhouses. The light from the traps did not increase the thrips population on the plants below the traps. The implications of the results for thrips control and suggestions for further studies are discussed.

1. Introduction

The western flower thrips, *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) is a major pest in a wide range of greenhouse crops (Lewis, 1997; Kirk and Terry, 2003), and can cause considerable direct damage through feeding, oviposition scars and virus transmission (EPPO/CABI, 1997). Many countries use biological control agents and insecticides as their primary control strategies, often combined in integrated pest management programs. The thrips' high reproductive capacity and cryptic feeding behaviour makes biological and chemical control challenging. Early detection and effective trapping is therefore crucial to obtaining satisfactory control (Brødsgaard, 1989; Vernon and Gillespie, 1990b; Roditakis et al., 2001, Roth et al., 2016).

Blue and yellow reflected light is attractive to *F. occidentalis*, and elicits a positive phototactic response towards the coloured object (Johansen et al., 2011b). This phenomenon is utilized in the use of blue and yellow sticky traps for monitoring of *F. occidentalis* in greenhouses (Yudin et al., 1987; Gillespie and Vernon, 1990; Roth et al., 2016). The capacity of these traps is, however, too low for practical and cost-effective mass trapping (Vernon and Gillespie, 1995; Broughton et al., 2015). One way to increase trap catches is to strengthen the thrips' positive phototactic response by making the visual signal from the traps more attractive.

The spectral sensitivity of darkness-adapted compound eyes of *F. occidentalis* has been found to peak at UVA (around 360 nm) and green (500-540 nm), and there is evidence for the existence of UVA and green absorbing photo-pigments (Matteson et al., 1992; Otani et al., 2014). It is, however, suggested that the spectral sensitivity curve of the compound eyes (Otani et al., 2014) and the phototactic response to reflected light from different coloured sticky traps (Vernon and Gillespie, 1990b) reflect the integration of the reaction of UVA (350-363 nm), blue (440-476 nm) and green (535-570 nm) absorbing photo pigments (Matteson and Terry, 1992). This would explain the strong behavioural positive response to blue-coloured objects and blue emitted light found in many studies (e.g. Brødsgaard, 1989; Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; Vernon and Gillespie, 1990b; Matteson and Terry, 1992; Roditakis et al., 2001; Chen et al., 2004; Chu et al., 2005; Makabe et al., 2014; Yang et al., 2015).

Choice experiments measuring phototactic movement of adult *F. occidentalis* towards point sources of emitted light in darkness have shown that the thrips are attracted to UVA (355-385 nm) (Chu et al., 2005; Makabe et al., 2014; Otani et al., 2014; Yang et al., 2015), blue (450-470 nm) (Makabe et al., 2014; Yang et al., 2015) and green (520-525 m) (Makabe et al., 2014; Otani et al., 2014; Yang et al., 2015). Yang et al. (2015) found that UV, blue (470 nm), green (520 nm) and yellow (590 nm) attracted more thrips than white (450-620nm), red (625 nm) and infrared (730 nm) emitted light. The attraction to the light source seems to be modified by light intensity within a certain range.

Several phototactic behaviour studies show that *F. occidentalis* is attracted to a wide range of reflected wavelengths. Most studies show that non or low UV-reflective (generally < 35 % at 365 nm), violet, blue, yellow and white traps are more attractive for the trips than other colours (Yudin et al., 1987; Brødsgaard, 1989; Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; Vernon and Gillespie, 1990b; Matteson and Terry, 1992; Vernon and Gillespie, 1995; Chu et al., 2000; Roditakis et al., 2001; Hoddle et al., 2002; Chen et al., 2004; Chu et al., 2006). Studies of the relative preference for blue, yellow and white in different crops have yielded various results (Mofitt, 1964; Yudin et al., 1987; Brødsgaard, 1989; Gillespie and Vernon 1990; Vernon and Gillespie 1990a; Vernon and Gillespie 1990b; Matteson and Terry, 1992; Cho et al., 1995; Chu et al., 2000; Roditakis et al., 2001; Hoddle et al., 2002; Chen et al., 2004; Chu et al. 2006; Roth et al. 2016). Different levels of UV-reflection and colour saturation and intensity of the coloured traps used in the studies, and different experimental conditions, such as crop type and cropping environments, may explain some of the inconsistencies in the thrips' colour response.

Blue has been found to be the most attractive colour to *F. occidentalis* in various greenhouse experiments (Brødsgaard, 1989; Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; Vernon and Gillespie, 1990b; Roditakis et al., 2001; Roth et al., 2016). Blue hues with maximum reflected wavelengths (λ_{max}) between 420 and 480 nm and a wavelength reflectance intensity (RI) from 36 and 63% were most attractive, and Vernon and Gillespie (1990b) found that the number of thrips caught increased with increasing RI within this range. Blue sticky traps caught more females relative to males than yellow traps (Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; 1990b), particularly at high thrips densities (Vernon and Gillespie, 1990b).

Sticky traps with bright yellow hues (RI > 80 % at wavelengths between 550 and 700 nm) and low UV reflection (10-20 %) are also attractive to *F. occidentalis* in greenhouse crops, although they may be less attractive than blue traps (Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; Vernon and Gillespie, 1990b; Roditakis et al., 2001; Roth et al., 2016). Yellow traps are, however, often preferred over blue traps by the growers because they also can be used to monitor other pests (Vernon and Gillespie, 1990a).

Some studies indicate that blue emitted light can increase catches of *F. occidentalis* on blue and yellow sticky traps. In Norwegian and Canadian greenhouses, the number of *F. occidentalis* caught on yellow sticky traps increased when the greenhouse light environment (daylight + high-pressure sodium lamps (HPSL)) was enriched with blue (cucumber) and blue and red (roses) wavelengths provided by light emitting diodes (LEDs) (Johansen et al., 2011a; Shipp et al., 2011). In southwestern USA, blue LEDs (λ_{max} 465 nm) added to blue sticky traps and operated during the night enhanced catches of *F. occidentalis* in greenhouse cage experiments with *Ranunculus asiaticus* L. (Chen et al., 2004) and alfalfa (Chu et al., 2005), and in field grown fava beans and cotton (Chu et al., 2005). Chen et al. (2004) suggest that blue sticky traps equipped with blue LEDs may be useful for monitoring and mass trapping in greenhouses.

In the present study, we aimed to determine whether trapping of *F. occidentalis* can be increased by adding blue LEDs to blue and yellow sticky traps in greenhouses. The trapping efficiency of different combinations of trap colour and light intensity and direction was evaluated from September to May in two commercial greenhouses in southern Norway, one with production of mixed non-flowering potted herbs (walls: polycarbonate plates, roof: glass) and one with production of *Alstroemeria* cut-flowers (walls and roof: acrylic plates). The implications of the results for thrips control and suggestions for further studies are discussed.

2. Material and methods

2.1. Traps and light

Blue sticky traps (10 x 20 cm) with 58 % reflectance at 450-465 nm and 13-29 % UV-reflectance (330-395 nm) (Blå fangplater, Borregaard Bioplant ApS, Denmark) and yellow sticky traps (10 x 25 cm) with 55 % reflectance at 570-590 nm and 8-11% UV-reflectance (330-395 nm) (Bug Scan sticky traps, Biobest Belgium NV, Belgium) were used. Their reflectance spectrum from 330 nm to 700 nm (Fig. 1) was measured with an integrating sphere (ISP-50-REFL OceanOptics, Eerbeek, Netherlands). A combined deuterium and halogen lamp (DH2000, OceanOptics) illuminated the sample via a 600 µm optical fibre connected to the sphere. The spectral reflectance was measured with a spectrometer (model SD2000, OceanOptics) connected to the output port of the sphere with a 400 µm thick fibre. The percentage reflection was calculated on the basis of a dark spectrum and a reference spectrum from a white reference tile (WS-2, OceanOptics). LEDs (LED strip SMD3528 IP65 4,8 W/m 12v 120^o, NORDESIGN AS, Trondheim, Norway) with a peak emission (λ_{max}) at 459 nm (Fig. 1) were mounted on one of the sticky surfaces of the traps. The LED spectrum was measured with an Optronic OL-756 spectroradiometer (Optronic Laboratories, Orlando, FL, USA). The LEDs were turned on 24 hours a day because we wanted to strengthen the visual signal from the traps during the most active flight period of the thrips, which normally occurs during daytime (Liang et al., 2010), and extend the trapping period into the dark period. Several action spectrum studies have shown that adult thrips fly towards point sources of blue emitted light in dark rooms (e.g. Makabe et al., 2014; Yang et al., 2015).

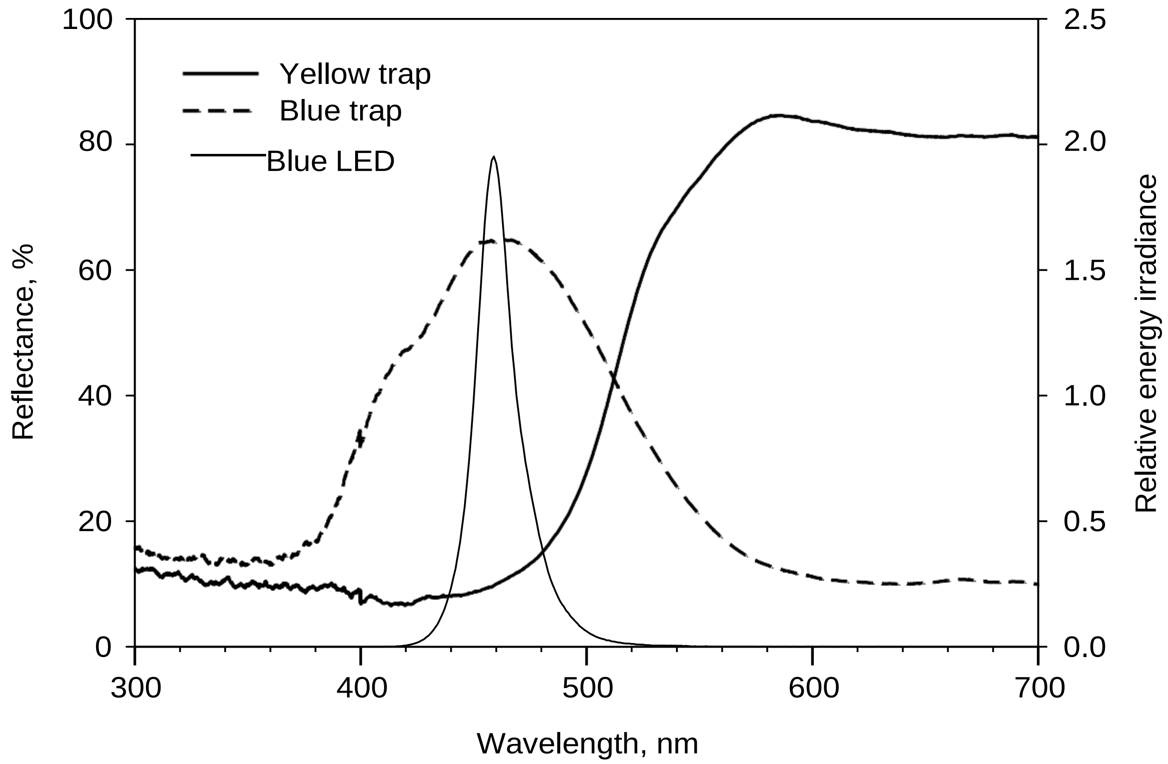

Figure 1. Reflectance from the blue and yellow sticky traps and relative spectral energy irradiance for the blue LEDs.

2.2.Trap evaluations in herbs

The herb greenhouse was located in South-West Norway (58° 44' N, 5° 33' E). The natural photoperiod at this location decreases from 13 hours in mid-September to 6 hours at winter solstice, and increases again to 17 hours in mid-May. The herbs were grown in pots on tables from seedling emergence until they were sold. *Frankliniella occidentalis* and other pests were controlled with biological control agents. Set points for heating and ventilation in the greenhouse were 20.0ºC and 20.5ºC, respectively. Artificial lighting with HPSL (SON-T Agro 400 W, 16 000 lux) was provided for 18 hours a day when the total solar radiation measured outside was < 300 W/m^2.

***2.2.1. Herbs, experiment 1, September-December*:** Six blue sticky traps types (Table 1, trap types BH-3D, BH-6D, BV-3D, BV-6D, BV-3S and BV-6S) with either 3 or 6 LEDs (0.24 or 0.48 W) were evaluated. The light direction was either downward (perpendicular to the plant canopy) or sideward (parallel to the plant canopy) on vertically oriented traps, or downward on horizontally oriented traps. Vertically and horizontally oriented blue traps without LEDs were used as control (Table 1, trap types BV-0 and BH-0). The traps were arranged randomly in rows above the plants along the center of each of ten randomly selected tables (1.9 x 8.3 m) in a 1000 m^2 greenhouse. Each of the eight trap types was represented once at each of the ten tables (80 traps, 10 replicates of each trap type). The tables contained non-flowering *Anethum graveolens, Origanum vulgare*, *Melissa officinalis*, *Petroselinum crispum*, *P. hortense* and *Thymus vulgaris*. The distance from the lower edge of the traps to the top of the plant canopy ranged from 10 to 30 cm, according to herb species and growth stage. The distance between the traps within and between the tables was 1 m and 6 to 18 m, respectively.

The number of thrips caught on the enlightened side of the traps was counted weekly for the first four weeks (high thrips density) and every second week for the next eight weeks (low thrips density). Number of thrips on the plants was measured at every trap counting. Three plants were randomly selected within a 1 m^2 plot below each trap. The plants were shaken over a white sheet of paper, and the number of thrips larvae and adults was immediately counted. Initial thrips infestation was measured on blue traps without light during one week before the LEDs were turned on, and on the plants below the traps the day before.

Table 1. Trap types evaluated for efficiency in trapping *Frankliniella occidentalis* in mixed potted herbs and *Alstroemeria* cut flower production. Number of replicates of each trap type is 10 in experiment 1, 2 and 3, and 20 in experiment 4.

Trap type	**Trap colour**	**Trap orientation**	**LED energy use, W per trap**	**Light direction**	**Crop**	**Exp. no.**
BH-0	Blue	Horizontal	0	-	Herbs	1
BH-3D	Blue	Horizontal	0.24	Downward	Herbs	1
BH-6D	Blue	Horizontal	0.48	Downward	Herbs	1
BV-0	Blue	Vertical	0	-	Herbs, *Alstroemeria*	1,2,3,4
BV-3D	Blue	Vertical	0.24	Downward	Herbs	1
BV-6D	Blue	Vertical	0.48	Downward	Herbs	1
BV-3S	Blue	Vertical	0.24	Sideward	Herbs	1
BV-6S	Blue	Vertical	0.48	Sideward	Herbs, *Alstroemeria*	1,2,3
BV-9S	Blue	Vertical	0.72	Sideward	Herbs, *Alstroemeria*	2,3
BV-12S	Blue	Vertical	0.96	Sideward	Herbs, *Alstroemeria*	2,3,4
YV-0	Yellow	Vertical	0	-	Herbs, *Alstroemeria*	2,3,4
YV-6S	Yellow	Vertical	0.48	Sideward	Herbs, *Alstroemeria*	2,3
YV-9S	Yellow	Vertical	0.72	Sideward	Herbs, *Alstroemeria*	2,3
YV-12S	Yellow	Vertical	0.96	Sideward	Herbs, *Alstroemeria*	2,3,4

***2.2.2. Herbs, experiment 2, January-May*:** Three blue and three yellow vertically oriented, light equipped sticky traps with either 6, 9 or 12 LEDs (0.48, 0.72 or 0.96 W) emitting blue light in a sideward direction were evaluated (Table 1, trap types BV-6S, BV-9S, BV-12S, YV-6S, YV-9S, and YV-12S), and compared to blue and yellow traps without light (trap type BV0 and YV-0). The traps were arranged in a similar way in the same greenhouse as in the previous experiment. Each of the eight trap types were represented once at each of the ten tables selected for the experiment (80 traps, 10 replicates of each trap type). The tables contained non-flowering *A. graveolens, O. vulgare, M. officinalis, P. crispum* and *T. vulgaris*. Thrips were counted on sticky traps and plants every second week (low thrips infestation) in the same manner as in experiment 1.

2.3. Trap evaluation in *Alstroemeria*

The greenhouse with *Alstroemeria* was located in South-East Norway (59° 21' N, 10° 43' E). At this location the natural photoperiod also decreases from 13 hours in mid-September to 6 hours at winter solstice, and increases again to 17 hours in mid-May. One white (‘Virginia’) and four red, pink or orange (‘Denver’, ‘Salmon Queen’, ‘Manilla’, ‘Victoria’) cultivars were grown in rows in soil beds on the greenhouse floor. Harvesting for sale was done daily by picking single shoots from the plant canopy as soon as the first flower of the inflorescence opened. Insecticides were the primary pest control method. Artificial lighting with HPSL (SON-T Agro 400 W, 12 000 - 13 000 lux) was provided for 18 hours a day when the total solar radiation measured outside was < 300 W/m^2. Set points for the heating and ventilation were 19.5^{o}C and 20.0^{o}C, respectively, during daytime, and 14^{o}C during the night.

***2.3.1. Alstroemeria, experiment 3, February-May*:** Three light equipped blue and three light equipped yellow vertically oriented sticky traps with 6, 9 or 12 LEDs (0.48, 0.72 or 0.96 W) emitting light in a sideward direction were used (Table 1, trap types BV-6S, BV-9S, BV-12S, YV-6S, YV-9S, and YV-12S). Blue and yellow traps without light (Table 1, trap types BV-0 and YV-0) were used as controls. The traps were arranged in rows above the plants along the center of ten out of 26 beds (15.0 x 1.1 m) in a 768 m^2 greenhouse. The eight trap types were placed randomly within the rows, and each trap type was represented once at each bed (80 traps, 10 replicates of each trap type). The distance between the traps within and between the beds was 1.7 m and 3.4-6.8 m, respectively. The lower edge of the traps was placed 10-20 cm above the top of the plant canopy. Five of the selected beds contained the coloured cultivars and the other five beds contained the white cultivar 'Virginia'. Number of thrips on traps and plants were counted every second week. Thrips density on the plants was estimated by randomly selecting three inflorescences in which the oldest bud was ready to open, from a 1.7 m^2 plot below each trap. The inflorescence was shaken over a sheet of white paper, and larvae and adult thrips were counted immediately. Initial thrips infestation was measured on blue and yellow traps without light and in the inflorescences during two weeks before the experiment started. Due to high thrips infestation, the grower treated the plants every 6-12 days with insecticides throughout the experimental period.

***2.3.2. Alstroemeria, experiment 4, September-December*:** The blue and yellow traps with 12 LEDs (0.96 W) (Table 1, trap type BV-12S and YV-12S) were further evaluated in the same greenhouse as in experiment 3, and compared to blue and yellow traps without light (Table 1, trap types BV-0 and YV-0). Trap placement and arrangement were similar to the previous experiment, except that each trap type was represented twice at each bed (80 traps, 20 replicates of each trap type. Thrips density was measured with blue and yellow traps without light and in the inflorescences during the preceding six weeks before the trap lights were turned on. Thrips on traps and plants were counted weekly or biweekly according to variations in thrips density, following the same procedure as in experiment 3. Insecticides were not used.

2.4. Statistics

The number of thrips caught on the traps was calculated per 100 cm^2 trap area to adjust for differences in trap size, and transformed to the response variable ln(no of thrips+1) to correct for heterogeneity of variances and obtain normal distribution. General Linear Model (GLM) (MINITAB® 16.1.0) procedures with $P<0.05$ as level of significance were used to determine main effects of trap type (trap and light orientation), trap colour and light. As far more thrips were found on plants and traps in the five beds with coloured *Alstroemeria* cultvars than in the five beds with the white cultivar before the LEDs were turned on in experiments 3 and 4, an unknown plant factor (called 'flower colour') was added to the data analysis. Where main effects were found, differences between level means were further analyzed by Tukey's Method with a 95 % confidence interval. The data are presented as back transformed means with corresponding standard error of means (SE).

3. Results

3.1. Herbs

***3.1.1. Herbs, experiment 1, September-December*:** The mean thrips density on the plants when the experiment started was 5.6 ± 0.8 thrips/3 plants. The population peaked the first week after the LEDs were turned on (6.7 ± 1.1 thrips/3 plants), and then dropped and remained low (between 2.2 ± 0.5 and 0.6 ± 0.2 thrips/3 plants) for the rest of the experimental period.

A main effect of trap type on number of thrips caught was found (Table 2) after the LEDs were turned on. Both trap orientation and presence of light affected the trap catches. In total over the experimental period, the vertically oriented traps caught far more thrips than the horizontally oriented ones, regardless of whether light was present or not (Figure 2). This pattern was rather consistent throughout the experimental period. At each light intensity level, the vertical traps caught 2.9 – 4.4 times more thrips than the horizontally oriented traps.

Table 2. Analysis of main effects of trap type, trap colour, light and interaction between trap colour and light on the total number of *Frankliniella occidentalis* trapped in herbs before and after the light on the traps were turned on. GLM, P<0.05 level of significance.

Lights off							
Exp. no.	**Crop**	**Factor**	**DF**	**F**	**P**	**R-Sq (adj)**	**DF_{error}**
1	Herbs	Trap type	7	1.77	0.109	70.0	63
2	Herbs	Trap colour	1	0.17	0.677	57.8	63
		Light	3	1.25	0.300		
		Trap colour*light	3	2.23	0.093		
Lights on							
Exp. no.	**Crop**	**Factor**	**DF**	**F**	**P**	**R-Sq (adj)**	**DF_{error}**
1	Herbs	Trap type	7	49.11	0.000	90.0	63
2	Herbs	Trap colour	1	55.24	0.000	68.9	63
		Light	3	11.60	0.000		
		Trap colour*light	3	2.69	0.053		

Adding light to the traps significantly increased the catches in five of the six trap types with LEDs (Figure 2). The horizontal traps with 3 and 6 LEDs caught about double the amount of thrips than the horizontal traps without LEDs. The vertical traps with 3 and 6 LEDs in a sideward direction and 6 LEDs in a downward direction caught between 1.7 and 2.3 times more thrips than vertical traps without LEDs. Traps with 6 LEDs caught consistently more thrips than the traps without light throughout the experimental period, except for the latest sampling date. There was a tendency of a positive response to the increase in light intensity.

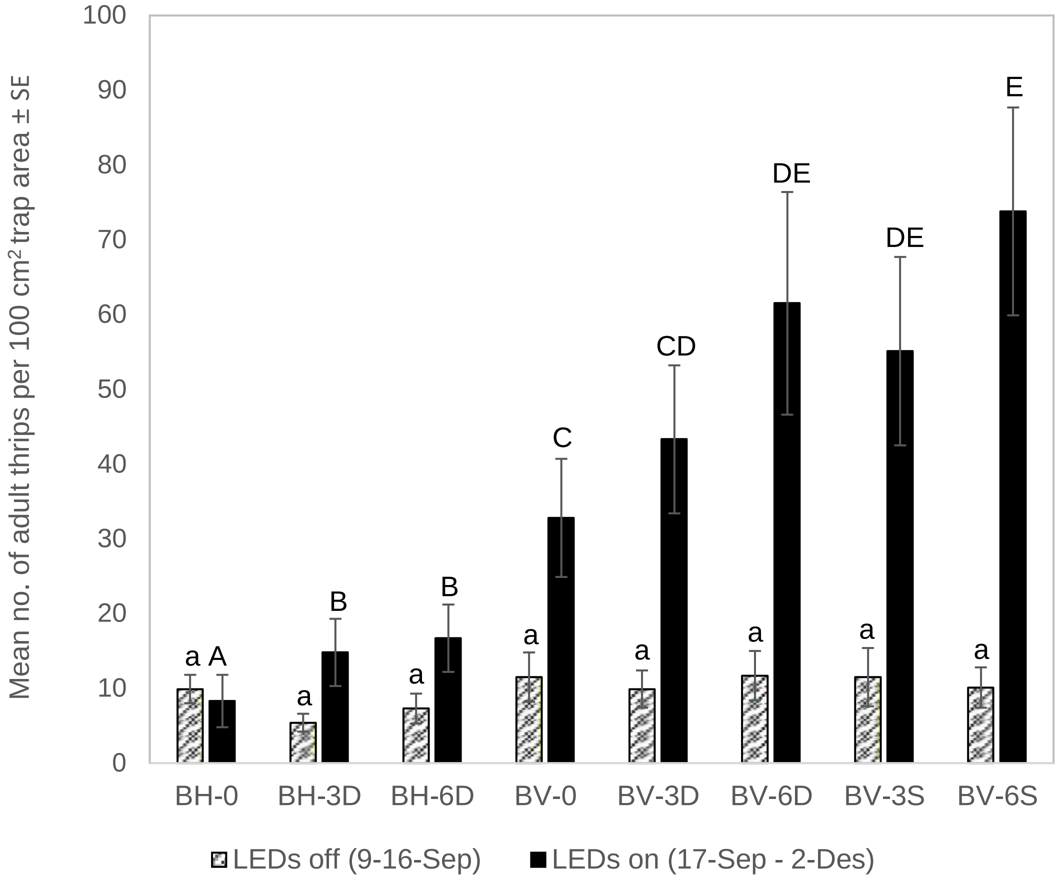

Figure 2. Herbs, experiment 1. Catches of *Frankliniella occidentalis* on vertical and horizontal blue sticky traps without LEDs (BH-0 and BV-0) and with 3 (BH-3D, BV-3D and BV-3S) or 6 LEDs (BH-6D, BV-6D and BV-6S) emitting blue light in a sideward or downward direction. Lower case and capital letters indicate differences in trap catches before and after the LEDs were turned on, respectively (Tukey method, $p < 0.05$).

***3.1.2. Herbs, experiment 2, January-May*:** The mean thrips density on the plants was very low both before and after the LEDs were turned on (between 0.1 ± 0.04 and 0.8 ± 0.2 thrips/3 plants). When the LEDs were on, main effects of trap colour and light were found, both when the number of thrips caught were pooled for the total experimental period (Table 2), and for most of the individual trapping periods. Between 1.7 and 2.7 times more thrips were found on blue traps than on yellow traps at the different light intensity levels (Figure 3). The trap catches tended to increase with increasing light intensity on the blue, but not on the yellow traps. Blue traps with 12 LEDs caught 2.5 times as many thrips in total than blue traps without light. This pattern was consistent throughout the experimental period, except for one sampling date.

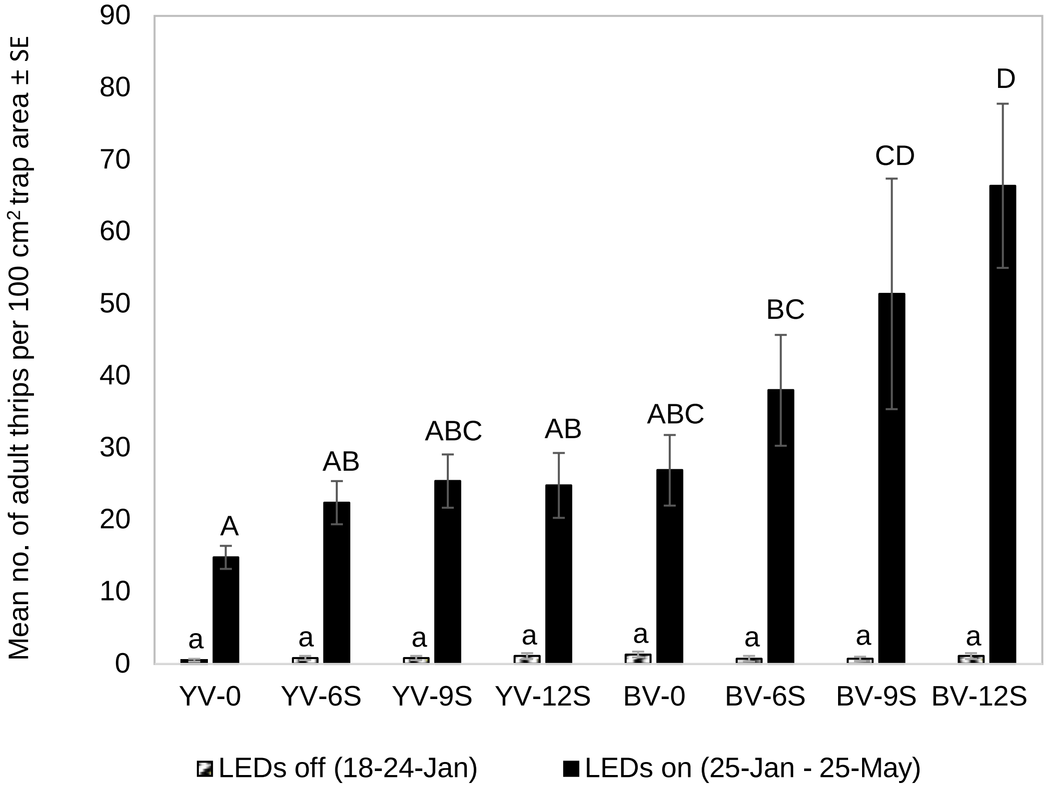

Figure 3. Herbs, experiment 2. Catches of *Frankliniella occidentalis* on vertical yellow (YV) and blue (BV) sticky traps without LEDs (YV-0 and BV-0) and with 6 (YV-6S and BV-6S), 9 (YV-9S and BV-9S) or 12 (YV-12S and BV-12S) LEDs emitting blue light in a sideward direction. Lower case and capital letters indicate differences in trap catches before and after the LEDs were turned on, respectively (Tukey method, $p < 0.05$).

3.2. Alstroemeria

***3.2.1. Alstroemeria, experiment 3, January-May*:** The mean initial thrips density in the inflorescens before the LEDs were turned on was 8.9 ± 0.5 and 4.0 ± 0.4 thrips/3 inflorescences on the coloured and white cultivars, respectively. When the LEDs were turned on, thrips density was still high, but the use of insecticides gradually reduced the population to < 0.3 thrips/3 inflorescences on both the coloured and white cultivars.

There were no main effects of light on the number of thrips caught after the LEDs were turned on (Table 3), but main effects of 'flower colour' and trap colour, and their interaction, were found. Within each 'flower colour', the blue traps were preferred by the thrips over the yellow ones, and there were far more thrips on the blue traps above the coloured cultivar group than in the other combinations of trap colour and 'flower colour' (Figure 4). This pattern was the same before the LEDs were turned on. The main effect of trap colour was found in five of the seven separate trapping periods after the LEDs were turned on, whereas the main effect of 'flower colour' and the 'flower colour' and trap colour interaction were only found before thrips density dropped to 0.3 thrips/3 inflorescences.

***3.2.2. Alstroemeria, experiment 4, September-December*:** Thrips density on the plants was low both before and after the LEDs were turned on (range 2.6 ± 0.4 to 0.8 ± 0.2 thrips/3 inflorescences).

Main effects of light, 'flower colour' and trap colour on number of thrips caught on the traps were found (Table 3), both when thrips numbers caught were pooled over the entire period with trap lights on, and for each trapping period. Light clearly increased thrips catches on both the blue and yellow sticky traps in both cultivar groups. The thrips catches on the light-equipped traps increased between 3.4 and 4.5 times for the different combinations of 'flower colour' and trap colour (range 1.2 – 8.9 times in each trapping period) compared to traps without light. Again, more thrips were caught on the blue traps than on the yellow traps, and more thrips were caught on the traps above the coloured cultivars than above the white cultivar (Figure 5). In the last three trapping periods, interactions were found between 'flower colour' and trap colour (two periods), 'flower colour' and light (two periods) and trap colour and light (last period).

Table 3. Analysis of main effects of trap colour, light and 'flower colour' and their interactions on the total number of *Frankliniella occidentalis* trapped in *Alstroemeria* before and after the light on the traps were turned on. Experiments 3 and 4. GLM, p<0.05 level of significance.

Lights off						
Exp. no	**Factor**	**DF**	**F**	**P**	**R-Sq (adj)**	**DF_{error}**
3	'Flower colour'	1	48.98	0.000	85.2	56
	Trap colour	1	93.37	0.000		
	Light	3	11.93	0.000		
	'Flower colour'*Trap colour	1	16.45	0.000		
	'Flower colour'*Light	3	5.82	0.002		
	Trap colour*Light	3	0.28	0.838		
	'Flower colour'*Trap colour*Light	3	0.37	0.778		
4	'Flower colour'	1	0.95	0.359	67.13	64
	Trap colour	1	131.02	0.000		
	Light	1	0.34	0.563		
	'Flower colour'*Trap colour	1	4.56	0.037		
	'Flower colour'*Light	1	0.69	0.408		
	Trap colour*Light	1	0.17	0.680		
	'Flower colour'*Trap colour*Light	1	2.10	0.152		

Lights on						
Exp. no	**Factor**	**DF**	**F**	**P**	**R-Sq (adj)**	**DF_{error}**
3	'Flower colour'	1	17.47	0.003	83.05	56
	Trap colour	1	99.90	0.000		
	Light	3	1.21	0.314		
	'Flower colour'*Trap colour	1	11.00	0.002		
	'Flower colour'*Light	3	0.80	0.501		
	Trap colour*Light	3	0.20	0.894		
	'Flower colour'*Trap colour*Light	3	0.91	0.444		
4	'Flower colour'	1	7.57	0.025	88.32	64
	Trap colour	1	148.88	0.000		
	Light	1	175.14	0.000		
	'Flower colour'*Trap colour	1	0.58	0.450		
	'Flower colour'*Light	1	0.00	0.999		
	Trap colour*Light	1	0.27	0.604		
	'Flower colour'*Trap colour*Light	1	1.83	0.181		

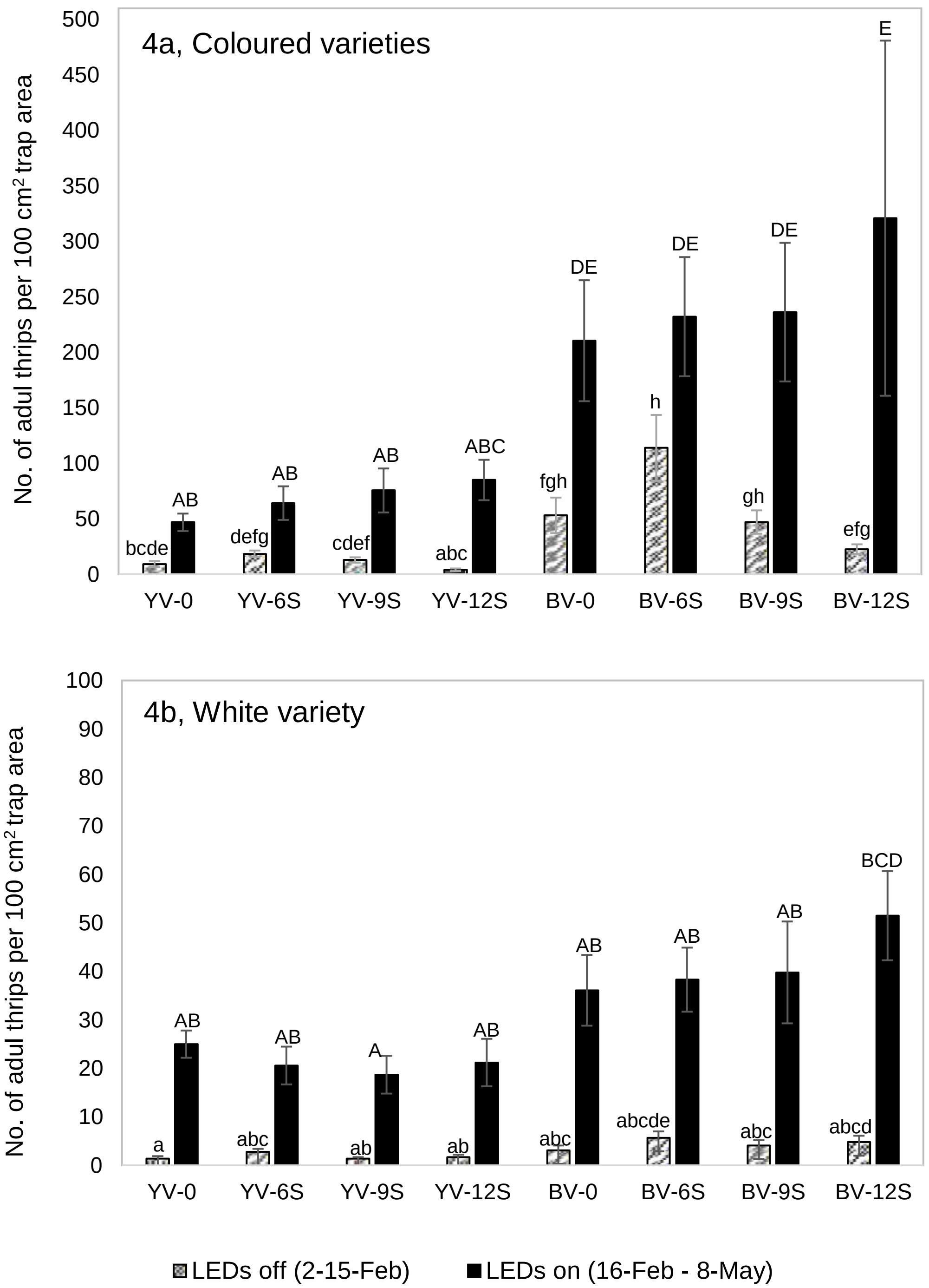

Figure 4. *Alstroemeria*, experiment 3. Catches of *Frankliniella occidentalis* on vertical yellow (YV) and blue (BV) sticky traps without LEDs (YV-0 and BV-0) and with 6 (YV-6S and BV-6S), 9 (YV-9S and BV-9S) or 12 (YV-12S and BV-12S) LEDs emitting blue light in a sideward direction in the coloured (4a) and the white (4b) *Alstroemeria* cultivars.

Lower case and capital letters indicate differences in trap catches before and after the LEDs were turned on, respectively (Tukey method, $p < 0.05$).

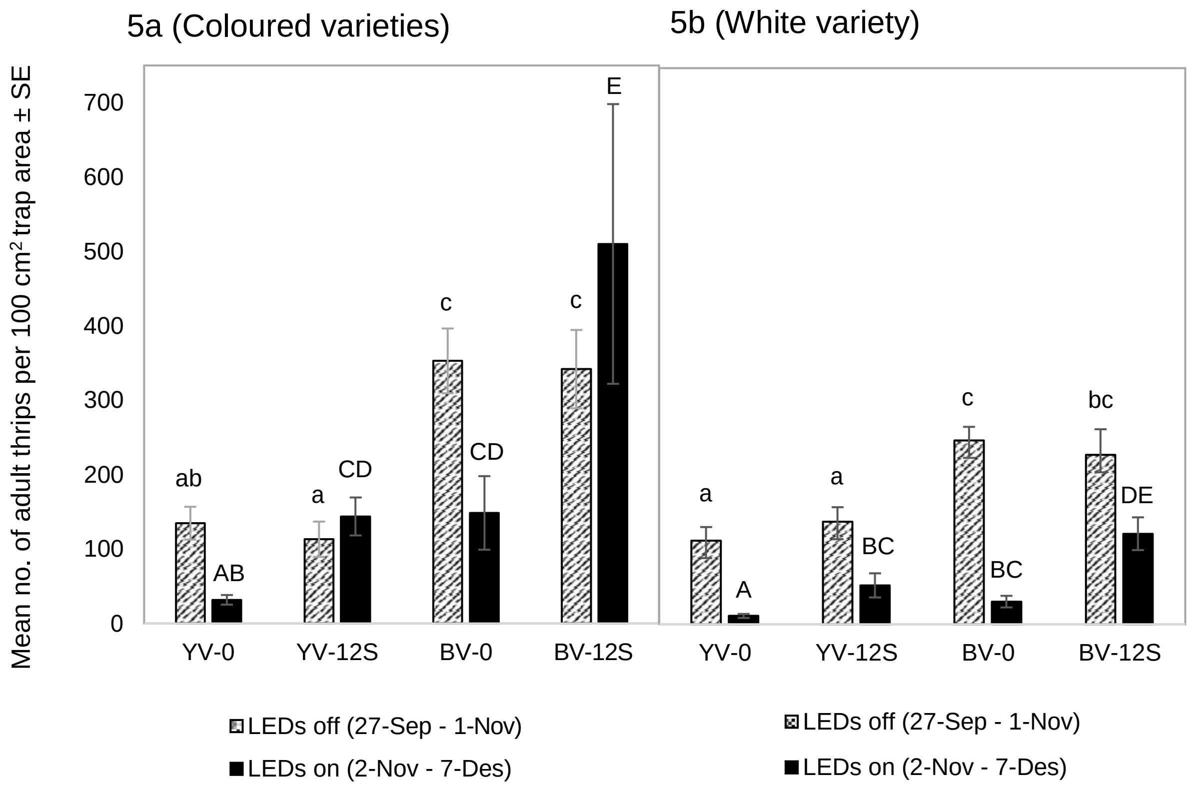

Figure 5. *Alstroemeria*, experiment 4. Catches of *Frankliniella occidentalis* on vertical yellow (YV) and blue (BV) sticky traps without LEDs (YV-0 and Bv-0) and with 12 LEDs (YV-12S and BV-12S) emitting blue light in a sideward direction in the coloured (5a) and the white (5b) *Alstroemeria* cultivars. Lower case and capital letters indicate differences in trap catches before and after the LEDs were turned on, respectively (Tukey method, $p < 0.05$).

4. Discussion

The blue traps generally caught more thrips than the yellow traps in both herbs and *Alstroemeria*, regardless of light or not. The preference for blue over yellow traps is consistent with several earlier greenhouse studies (Brødsgaard, 1989; Gillespie and Vernon, 1990; Vernon and Gillespie, 1990a; Vernon and Gillespie, 1990b; Roditakis et al., 2001; Roth et al., 2016). According to Vernon and Gillespie (1990a), thrips catches on yellow traps tend to be less predictable than catches on blue traps. Vernon and Gillespie (1990b) suggested that landing on yellow traps is stimulated by high wavelength-specific reflectance (>80 %) at wavelengths between 550 - 650 nm and low UV reflectance of approximately 20 % at 350-400 nm. The yellow traps used in the present study had lower UV-reflectance (8-11 % at 330-395 nm) and 50-55 % reflectance at 570-650 nm, which, at least partly, could explain why these traps were less attractive than the blue ones.

In *Alstroemeria*, the preference for blue over yellow seemed to be stronger over the coloured cultivar group than over the white cultivar, which indicates that the relative colour preference of thrips may be affected by properties of the plant. It is suggested that *F. occidentalis* uses both visual and odour cues to find its host (Matteson and Terry, 1992; Teulon et al., 1999). The combined response to colour and scent is not fully understood, but it is likely that different visual and chemical signals from different crops and cultivars influence the thrips' response to the traps.

The addition of blue light emitting light in a sideward direction increased thrips catches on the vertical blue sticky traps by 1.7 (3 LEDs) to 2.5 (12 LEDs) times in herbs, and by 3.4 and 4.0 (12 LEDs) times in the coloured and white cultivar groups, respectively, in one of the two experiments with *Alstroemeria*. Similar results from other evaluations of blue sticky traps with blue LEDs have been obtained in cages with *Ranunculus* (Chen et al., 2004) and alfalfa (Chu et al., 2005) in greenhouses, and in fields with fava bean and cotton (Chu et al., 2005). On the other hand, blue LEDs did not increase catches of *F. occidentalis* in CC-traps (transparent cups with the open end facing downwards and fitted into a blue coloured base with a cylinder shape outside and hollow cone inside surface) in alfalfa fields (Chu et al., 2006). In the experiments with herbs, there seemed to be a positive correlation between numbers of thrips caught and light intensity on the blue traps, within the intensity range tested. Such a relationship was also found in the phototactic studies of Otani et al. (2014) and Yang et al. (2015), which showed that the attraction of *F. occidentalis* to blue emitted light in a dark room increased with increasing light level within a certain range. In contrast to the other experiments, no effect of adding blue light to blue traps was found in the first *Alstroemeria* experiment. The reason for this is not clear, but the weekly treatments with insecticides throughout the experimental period reduced the thrips population to a very low level. The spray program might also have caused lower thrips' flight activity or made the traps less attractive for the thrips.

Adding blue light to the yellow traps tended to increase thrips catches slightly compared to yellow traps without light in herbs and in the coloured cultivar group in the first *Alstroemeria* experiment, and resulted in about 4.5 times higher thrips catches in both cultivar groups in the second *Alstroemeria* experiment. The thrips' attraction to the yellow traps with LEDs was, however, equal to or only slightly higher than to blue traps without light, and lower than to blue traps with LEDs. The response to the increase in light intensity on the yellow traps seemed to be weaker than on the blue traps. One reason for this may be that much of the blue LED light was absorbed by the yellow traps, whereas the blue LED light was reflected by the blue traps, thereby strengthening the total blue signal from the light-equipped blue traps. Previous studies have shown that enriching the greenhouse light environment with blue or a combination of blue and red light from LED lamps increased catches of *F. occidentalis* on yellow sticky traps in rose and cucumber greenhouses during autumn, winter and spring in Norway and Canada (Johansen et al., 2011a; Shipp et al., 2011). A possible explanation for this could be that the blue light from the lamps elicited flight in the thrips and attracted them to the area in the greenhouse with enriched blue light. Vernon and Gillespie (1990b) showed, however, that a certain amount of blue reflected wavelengths stimulated landing of *F. occidentalis* on blue and other coloured sticky traps in greenhouse cucumbers, except on yellow traps where blue wavelengths seemed to inhibit landing.

The results of the present study suggest that blue light has the potential to increase thrips catches on blue sticky traps in herbs and *Alstroemeria* in commercial greenhouse production. The trapping efficiency of the traps varied, however, with experiment, crop and *Alstroemeria* cultivar group. The reason for this variation is not clear. The insect's response to visual cues can be modified by several factors, such as their physiological state and behavioral mode, visual and odour cues from their host-plant, aspects of the surrounding physical environment and the ways in which the visual cues are presented to them (Johansen et al., 2011b). It has been shown that the flight response of *F. occidentalis* to coloured traps can be affected by starvation, pregnancy, swarming, aggregation and flight activity (Matteson and Terry, 1992; Liang et al., 2010), sex (Gillespie and Vernon, 1990; Vernon and Gillespie, 1990b; Roditakis et al., 2001), thrips density in the crop (Vernon and Gillespie, 1990a; Cho et al., 1995; Chu et al., 2005); colour hue, satiation and brightness/intensity of the reflected light from the traps (Yuidin et al., 1987; Brødsgaard, 1989; Vernon and Gillespie, 1990b; Matteson and Terry, 1992; Roditakis et al., 2001; Roth et al., 2016), degree of UV-reflectance from the traps (Vernon and Gillespie, 1990b; Matteson and Terry, 1992; Roth et al., 2016), the traps' contrast to the background (Vernon and Gillespie, 1995), factors that influence the spectral composition and intensity of the reflected light from the traps like weather (Liang et al., 2010), type of light source that illuminates the traps (Matteson and Terry, 1992; Johansen et al., 2011a; Shipp et al., 2011b, Otani et al., 2014; Yang et al., 2015), cardinal direction of the trapping surface (Vernon and Gillespie, 1995; Teulon et al., 1999), placement of the traps in the crop according to crop height

(Brødsgaard, 1989; Gillespie and Vernon, 1990; Roditakis et al., 2001), temperature (Liang et al., 2010; Makabe et al., 2014) and relative air humidity (Liang et al., 2010). Hoddle et al. (2002) suggested that visual characteristics and resources offered to the thrips by the host plants in which the traps are used could affect the colour preference in polyphagous species like *F. occidentalis*, as was indicated also in the present study. The thrips' response to light equipped traps is likely to change more or less with shifts in the above-mentioned factors, and with differences in production procedures like insecticide use, pruning, harvesting, etc. in the greenhouses as well.

Further studies are needed to reveal which factors have major impact on the efficacy of the light traps in different crop production systems. To achieve this, we also need a better understanding of the visual system and behavior of *F. occidentalis*, and of how the thrips perceive, process, interpret and respond to light signals from the traps within the multiple array of light and other signals that they receive in the crop. To be effective, the traps have to overrule attractive and arresting plant signals. Increased attraction to the traps could be achieved by strengthening the visual cues that elicit directed movement towards and landing on the traps, perhaps in combination with semiochemicals that have been found to increase attraction of *F. occidentlis* to traps (e.g. Teulon et al., 1999; Koschier et al., 2000; Broughton et al., 2015).

Large-scale trials under commercial conditions are needed in order to evaluate the efficacy of light traps in non-choice situations, and through all seasons of the year. Besides being more attractive than plant signals, the light signals from the traps have to compete with those from daylight as well (Shimoda and Honda, 2013). The present experiments were conducted during autumn, winter and spring at a high latitude, with short to medium day lengths and low daylight intensity during the major part of the experimental periods. The efficiency of the traps should also be evaluated during summer with its higher light intensity. The possibility to timely boost thrips flight by manipulating the greenhouse climate and light environment within limits acceptable for crop production should also be considered. In our experiments, the temperature was around 20°C, a temperature where thrips flight activity according to Makabe et al. (2014) and Liang et al. (2010) is relatively low.

Use of light traps in commercial greenhouse production must not increase thrips damage in the crop, interfere with plant growth and development or obstruct pest control. No clear evidence of increased thrips densities on the plants below the traps with light was found in the present experiment. The risk of attracting thrips to the plants as well as to the traps must, however, be studied more closely. Even relatively low intensities of blue light may affect photoperiodic responses in the plants (Vänninen et al., 2010), and the effect of the spectral distribution, light intensity and timing of the trap-light needed for effective thrips trapping must be assessed for possible effects on the crop. The effect of blue light on thrips' natural enemies has been studied very little, but may affect a range of biological parameters such as phototactic behaviour and diapause induction, depending on the species (Johansen et al., 2011b). Any effects of light traps on biological control agents should therefore be evaluated to ensure their compatibility with biological control.

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