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Ecology and Behavior

Improved Light Traps for Early Detection of Insect Pests of Phytosanitary Concern in Shipping Containers

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Abstract

The number of introductions of alien insect has been increasing in the last decades, primarily transported in shipping containers. The attraction of light of different wavelengths (white, infrared, ultraviolet, and red) applied on sticky traps was tested for the development of new traps for hitchhiker insects. The addition of entomological glue and insecticide on the trap was also tested. Tests were conducted on *Cadra cautella* Walker (Lepidoptera: Pyralidae), *Drosophila melanogaster* Meigen (Diptera: Drosophilidae), *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae), and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) and released inside a shipping container. In the first test, one light color at a time was tested setting eight traps in the container, one for each possible combination of the variables: light on or off, glue added or not, and insecticide sprayed or not. In the second, five traps were used, all of them coated with the entomological glue: one for each light color and one with light off as control. In all the single color tests (except for infrared), light-on traps captured more, except for *T. castaneum* that was not attracted to white. In the multi-color test, *C. cautella* showed no preference among white, ultraviolet, or red; *Drosophila melanogaster* preferred ultraviolet and white over red; and beetles had a much greater attraction to red. Lastly, the stronger entomological glue improved catches of beetles, whereas insecticides did not. In conclusion, results suggest a possible application of sticky light traps against hitchhiker insects and further studies should verify if the simultaneous use of different light colors can improve the trap performance and does not act as a repellent.

Key words: alien species, interception, Coleoptera, Lepidoptera, Diptera

Introduction of non-native pests into new territories is a problem that has become of primary importance: driven by trade globalization, the rate of new introductions is increasing year by year (Bertelsmeier *et al.* 2017, Seebens *et al.* 2017). In the last centuries, human action has decisively facilitated and increased the processes of settlement of alien species outside their natural range (Hulme *et al.* 2008, Liebhold and Tobin 2008), with arthropods, and especially insects, considered as the most common and damaging group of invaders (Bradshaw *et al.* 2016). Invasion science is increasingly recognizing human-mediated dispersal as a pivotal node (Ricciardi *et al.* 2017, Bullock *et al.* 2018), demonstrating that the number of new biological invasions is closely related to the increase in international trade (Levine and D'Antonio 2003, Westphal *et al.* 2008). The most widely used means in international trade are shipping containers, which account for about 90% of global trade (IMO 2012, Bernhofen *et al.* 2016).

To try preventing and reducing new introductions, several international agreements have been signed such as the World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures (SPS), the International Plant Protection Convention (IPPC) of the Food and Agricultural Organization of the United Nations, and the Convention for Biological Diversity (CBD). All these agreements are based on the assumption that prevention is the most economically sound way to manage biological invasions (Puth and Post 2005, Bogich *et al.* 2008, Hulme *et al.* 2009). Nevertheless, there are many major gaps in the regulatory framework for the management of invasive insects, mainly dealing with the difficulty in assessing the effect of potential preventive measures implemented to reduce the risk of new introductions (Hulme *et al.* 2008, Hulme 2009). In addition, due to the huge volumes of goods passing through points-of-entry every day, phytosanitary inspectors can only check a small part of the commodities, with increasing

difficulties in selecting the loads to be sampled (Everett 2000, NRC 2002, Surkov *et al.* 2008).

The work of phytosanitary inspectors is a part of the *border surveillance*, applied at the point-of-entry, in order to prevent the settlement of alien species at the initial stage of their possible invasion process (Hulme 2014). In recent years, many tools and techniques have been tested to increase the effectiveness and efficiency of visual inspections (Augustin *et al.* 2012, Poland and Rassati 2019). Traps activated with pheromones, or volatiles, or other lures (e.g., light and colors) are the most common tools used in bio-surveillance programs, besides sniffer dogs, electronic noses, genetic tools for barcoding, acoustic detection, and laser vibrometry (Augustin *et al.* 2012, Poland and Rassati 2019). However, baited traps have a limit linked to the specificity of the pheromones used, which are often active only against one or a few species (Augustin *et al.* 2012, Rassati *et al.* 2015, 2019). Moreover, pheromone traps are active only during the flight dispersal of the insects in the new area, when adults have already left infested goods and containers. Therefore, traps baited using generic visual (Olenici *et al.* 2001, Sakalian and Mario 2004) or luminous stimuli (Ndengué *et al.* 2019, Silva *et al.* 2019) may have very high potentials in the early detection of unknown alien insect species arriving in international points-of-entry, especially when used inside the containers, i.e., before insect dispersal (Marchioro *et al.* 2020).

In the field of luminous stimuli, insects can be attracted (positive phototaxis) or repelled (negative phototaxis) to special light sources (Park and Lee 2017). Although the use of light is already widespread in integrated pest management (Garstang 2004), there is still no large scale application of light traps for the interception of alien species. In general, the vision of insect pests ranges from a wavelength of 350 nm (ultraviolet) to 700 nm (red; Land 1997). In light traps, incandescent or mercury vapor light bulbs are widely used, but LEDs (light emitting diodes) have been used increasingly in recent times (Oh 2011, Mangan and Chapa 2013, Park and Lee 2016). The advantages of LEDs are numerous and include small size, low weight, low electricity consumption, long lifetime, low temperature, high luminous efficiency, selectivity of specific wavelength, and light intensity (Cohnstaedt *et al.* 2008, Yeh and Chung 2009).

Widely used in agricultural systems (Oh 2011, Park and Lee 2016), light traps were also tested in border surveillance for the interception of pests transported with goods inside containers (Mangan and Chapa 2013, Marchioro *et al.* 2020). A research conducted by Marchioro *et al.* (2020) tested a light trap model inside a container, under different loading conditions, on four model species: *Cadra cautella* Walker (Lepidoptera: Pyralidae), *Drosophila melanogaster* Meigen (Diptera: Drosophilidae), *Sitophilus zeamais* Motschulsky, and *Ips typographus* L. (Coleoptera: Curculionidae). Results showed that trap performance is not affected by the container load and a high number of catches were recorded for Diptera and Lepidoptera. Instead, the trap was scarcely effective against beetles as the glue of the sticky cards of the trap was not strong enough to catch these insects, but a low attractiveness of the light installed in the trap also cannot be excluded. Results of this research have been encouraging and positive, but have also highlighted some gaps to be filled and improvements to be made on traps to improve their performance and effectiveness against more species. In view of these first results, the aim of this study was to investigate 1) how model species belonging to different insect orders respond to different light colors (i.e., wavelength), and 2) whether the synergistic use of more powerful glue and contact insecticides would improve capture performance of traps compared to the use of sticky cards only. This aims

to develop a generic light trap efficient in early detection of alien insects belonging to different orders and families.

Materials and Methods

Tested Traps

Light-sticky traps (TransTrap, Alpha Scents Inc., West Linn, OR) developed for use inside containers during shipment were modified as shown by Marchioro *et al.* (2020). The original device consists of a small carton box (15 × 23 × 4 cm) containing a LED to attract insects and a yellow sticky card to catch them. The LED is powered by two AA batteries that can keep the light on for at least two consecutive weeks. The sticky card is attached to the bottom of the box and the light is positioned in the center. To increase the sticky surface and, consequently, the catching performance of the trap, we attached a second sticky card inside the box lid (Fig. 1). Sticky cards are produced by Alpha Scents Inc. too, and they are a standard model mainly indicated against flies, aphids, hoppers, psyllids, and yellow jackets (Alpha Scents Inc. 2013) and, also considering results obtained by Marchioro *et al.* (2020), they probably are not stronger enough in order to capture beetles.

A standard LED emits light that has two peaks, one at 465 nm (indigo) and the second between 525 and 600 nm (between green and yellow) and the result is white light. Beside the original trap model, in this study, we also replaced the manufacturer's LED with LEDs of other three wavelengths: ultraviolet (wavelength 410 nm), red (wavelength 625 nm), and infrared (wavelength 940 nm). In order to prevent beetles from escaping, the inside surfaces of traps were also sprinkled with a strong entomological glue (Temo-O-Cid, Adama Italia s.r.l., Bergamo, Italy) and a solution composed by 1 ml of deltamethrin-based insecticide (Decis 15 EW, Bayer AG, Leverkusen, Germany) per 1 liter of water. Temo-O-Cid is a specific glue for the capture of flies and insects that can be spread with a brush. Once applied, the evaporation of the solvent contained makes the product absolutely nontoxic. It does not dry and retains its characteristics even when exposed to atmospheric agents. Temo-O-Cid is used to prepare chromotropic and all kinds of traps, to catch insects in orchards, vineyards, and flower crops. The greater strength of this glue, combined with a greater thickness of glue on the sticky card after its addition, should make it easier to catch larger insects.



Fig. 1. TransTrap, the trap used for the research.

Model Species

The different trap models were tested against four model species belonging to Coleoptera, Lepidoptera, and Diptera orders, the three most common orders found inside shipping containers (Meurisse *et al.* 2019). *Sitophilus zeamais*, the maize weevil, is one of the major pests of stored maize in tropical and temperate regions of the world, but it also infests other cereals as alternative hosts (Erenso and Berhe 2016, Nwosu 2018). *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), the red flour beetle, is a stored grain, flour, and other cereal product pest (Brown *et al.* 2009). *Cadra cautella*, the almond moth, is a pest of cereal grains, beans, and other dried seeds (Aldawood *et al.* 2013, Husain *et al.* 2017). *Drosophila melanogaster* is a fruit and vegetable pest (Mallis 1954, Birmingham *et al.* 2011).

All insects were provided by a laboratory (Entostudio s.r.l., Padua, Italy) specialized in the breeding of arthropod species for scientific purposes. The colony of *S. zeamais* was established in 2014 with insects collected in the field. Adults were bred in plastic cups enclosed by a net and fed with grain. The photoperiod lasted 12 h at a solar spectrum artificial light of 6,000 K and 300 lux intensity and they were bred at $25 \pm 1^\circ\text{C}$ and $50 \pm 5\%$ RH. Similarly, adults of *T. castaneum* were bred in plastic cups enclosed by a fine net, at $25 \pm 1^\circ\text{C}$ and $50 \pm 5\%$ RH. The photoperiod, at a solar spectrum artificial light of 6000 K and 300 lux intensity, lasted 14 h. Insects were fed with 95% of flour and 5% of beer yeast and a vial filled with water was present in the plastic cup to provide water and humidity to the colony. Adults of *C. cautella* were bred in glass jars positioned upside down with the opening closed by a 2-mm mesh net. The jar was placed above a plastic container to collect the eggs, which were then moved daily into plastic cups containing a mixture of wheat and corn flour, oat, bran, dry fruit, glycerol, honey, and yeast. The insects were reared at $25 \pm 1^\circ\text{C}$ and $50 \pm 5\%$ RH. The photoperiod, at a solar spectrum artificial light of 6,000 K and 300 lux intensity, lasted 12 h. Adults of *D. melanogaster* were bred in BugDorm cages. A mixture of water, pieces of potato and fruit, powdered milk, and sugar was used as food and as an oviposition substrate. Insects were reared at $25 \pm 1^\circ\text{C}$ and $50 \pm 5\%$ of RH with a photoperiod of 12 h at a solar spectrum artificial light of 6,000 K and 300 lux intensity.

All insects were tested only once and within 2 d after their emergence (for *C. cautella* and *D. melanogaster*) to guarantee highest vitality. We assumed a sex-ratio 1:1 as these four species reproduce sexually and produce a sex-balanced offspring (Englert and Bell 1962, Santos *et al.* 1994, Danho *et al.* 2002, Soffan *et al.* 2012). The insects used in each trial were chosen randomly.

Trials in Container

Trials were conducted in an ISO standard shipping container 1CC (interior size: 5.8 m length, 2.3 m width, and 2.3 m height; ISO 2013). The container was placed in the Agripolis Campus, University of Padua (Legnaro, Italy), without any shelter from sun and rain. The container was empty of goods and only the traps and insect-releasing device were placed inside. In contrast to the tests conducted the year before (Marchioro *et al.* 2020), in this case, no container load tests were carried out, as the aim of the study was to test the attractiveness of different wavelengths. Traps were positioned inside the container open, with lid and box forming a 90° angle. The lid was resting on the ground while the box was in a vertical position, as can be seen in Fig. 1. In trials in which some traps had to be placed on the top of the container, the use of metal hooks made it possible to maintain the same conformation as traps placed on the ground. Tests were conducted between May and July 2020.

Single Color Tests

The first group of tests was conducted using only one light color at a time. We used eight different traps at the same time, one for each of the eight possible combinations of the three considered variables: light (turned on or off), additional glue (added or not), and insecticide (sprayed or not). A trap with a turned off light and without additional glue or insecticide was used as control (trap 'C'). Each different combination of variables corresponds to a different code: 'L' if the trap light was on, 'G' if glue was added, and 'I' if insecticide was added. The eight traps were randomly set in the eight corners of the container (changing the traps arrangement at each trial; Fig. 2): four traps were laid on the ground while four were hung by hooks from the ceiling. During each trial, we used 50 individuals for each model species released at the same time, for a total of 200 insects. With a device consisting of a cup containing the insects and a rope tied to the lid to free them, it was possible to release the insects just before the doors of the container were closed to prevent their escape. For each LED color (white, infrared, ultraviolet, and red), we conducted seven repetitions, on seven consecutive nights with similar weather conditions; each repetition lasted 18 h (from 05:00 p.m. to 11:00 a.m. the following day). At the end of each trial, before starting a new one, we ventilated the container, swept the floor, and removed all insects from the walls to make sure there were none left inside.

Multicolor Tests

Other tests were conducted using, at the same time in the container, all traps with the four different light colors. One trap per light color (white, red, ultraviolet, and infrared) and coated with entomological glue was tested, whereas a trap with a turned off light and without additional glue was used as control (trap 'C'). Again, each different light color corresponds to a different code: 'W' for white light, 'IR' for infrared light, 'UV' for ultraviolet light, and 'R' for red light. The five traps were randomly set inside a container, on the floor (changing the traps arrangement at each trial; Fig. 2). Seven repetitions were conducted on seven consecutive nights, with duration of 18 h (from 05:00 p.m. to 11:00 a.m. the following day). Fifty individuals per model species were used in each repetition, for a total of 200 insects per day.

Statistical Analysis

In the 'single color tests', mean catches per trap of the model species were compared using a mixed-effect model, with trap type (the eight possible combinations of the three tested variables) as a fixed

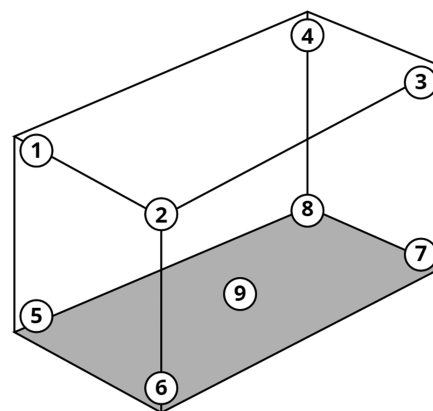


Fig. 2. Disposition of the traps inside the container (doors were on the left side). Single color test: 1–8. Multicolor test: 5–9.

variable and repetitions as a random variable. The model was fitted using the 'lmer' or 'glmer' functions in the lme4 package (Bates *et al.* 2015) and using Poisson distribution or logarithmic transformation as appropriate (Table 1). Multiple comparisons between fixed variables were obtained using Tukey's test ('emmeans' function in the emmeans package) with 'Bonferroni correction' (Russell 2019). When the use of this statistical test was inapplicable because of few captures, the Kruskal–Wallis test was applied using the 'kruskal.test' function in the stat package (R Core Team 2019).

In the 'Multi color tests', mean catches per trap of the model species were compared using a mixed-effect model, with trap type (the five light colors, including control) as a fixed variable and repetitions as a random variable; Tukey's test with 'Bonferroni correction' was used for multiple comparisons between fixed variables. Statistical analysis was performed using R software, version 3.6.1 (R Core Team, 2019).

Results

The main obtained results are presented here briefly according to the tested light color. The number of captures for each model species in each test is reported in Supp Table S1 (online only).

Single Color Test—White Light

The four trap combinations with light turned on (trap L, L + G, L + I, and L + G + I) caught similar numbers of *C. cautella* and significantly higher than the light-off traps (C, G, I, and G + I; Table 1; Supp Table S2 [online only]; Fig. 3a). The same result was observed for *D. melanogaster*, although in this species trap L captured significantly more individuals than L + G (Table 1; Supp Table S2 [online only]; Fig. 3b). *Sitophilus zeamais* was captured significantly more in traps L + G and L + G + I than all the others. Moreover, in *S. zeamais* the other two light-on traps (L and L + I) caught significantly more than light-off traps (Supp Table S3 [online only]; Fig. 3c). Only one

Table 1. Results of the statistical models (*P*-value) used to test the effect of trap type for the four model species in all the tests conducted

Model species	Trap type	<i>P</i> -value	t/z-value	df	Model	Distribution
Single color test—White light						
<i>Cadra cautella</i>	L	<0.001	9.303	48	LMM	Normal
	L + G	<0.001	7.048			
	L + I	<0.001	7.330			
	L + G + I	<0.001	7.893			
<i>Drosophila melanogaster</i>	L	<0.001	4.878	47	GLMM	Poisson
	L + G	<0.001	3.826			
	L + I	<0.001	4.334			
	L + G + I	<0.001	4.366			
Single color test—Infrared light						
<i>Cadra cautella</i>	–	–	–	47	GLMM	Poisson
<i>Drosophila melanogaster</i>	–	–	–	47	GLMM	Poisson
Single color test—Ultraviolet light						
<i>Cadra cautella</i>	L	<0.001	3.660	48	LMM	Normal
	L + G	<0.01	3.253			
	L + I	<0.01	3.186			
	L + G + I	<0.01	3.253			
<i>Drosophila melanogaster</i>	L	<0.001	4.369	47	GLMM	Poisson
	L + G	<0.001	4.872			
	L + I	<0.001	5.546			
	L + G + I	<0.001	6.097			
Single color test—Red light						
<i>Cadra cautella</i>	L	<0.01	3.254	47	GLMM	Poisson
	L + G	<0.01	3.254			
	L + I	<0.001	3.531			
	L + G + I	<0.001	4.542			
<i>Drosophila melanogaster</i>	L	<0.001	4.777	48	LMM	Log-transf.
	L + G	<0.001	4.245			
	L + I	<0.001	5.552			
	L + G + I	<0.001	5.098			
Multi-color test						
<i>Cadra cautella</i>	UV	<0.001	3.791	24	LMM	Normal
<i>Drosophila melanogaster</i>	W	<0.001	6.732	29	GLMM	Poisson
	UV	<0.001	5.988			
<i>Sitophilus zeamais</i>	R	<0.001	4.159			
	W	<0.001	5.727	24	LMM	Log-transf.
	UV	<0.01	3.279			
	R	<0.001	10.370			
<i>Tribolium castaneum</i>	W	<0.05	2.621	24	LMM	Log-transf.
	UV	<0.001	7.474			
	R	<0.001	13.131			

L = light on; G = glue added; I = insecticide sprayed.

Models = LMM: linear mixed-effects model; GLMM: generalized linear mixed-effects model; Distribution = Normal: normal distribution; Log-transf.: normal on log-transformed data; Poisson: Poisson distribution. *t*-value is referred to LMM models; *z*-value is referred to GLMM models.

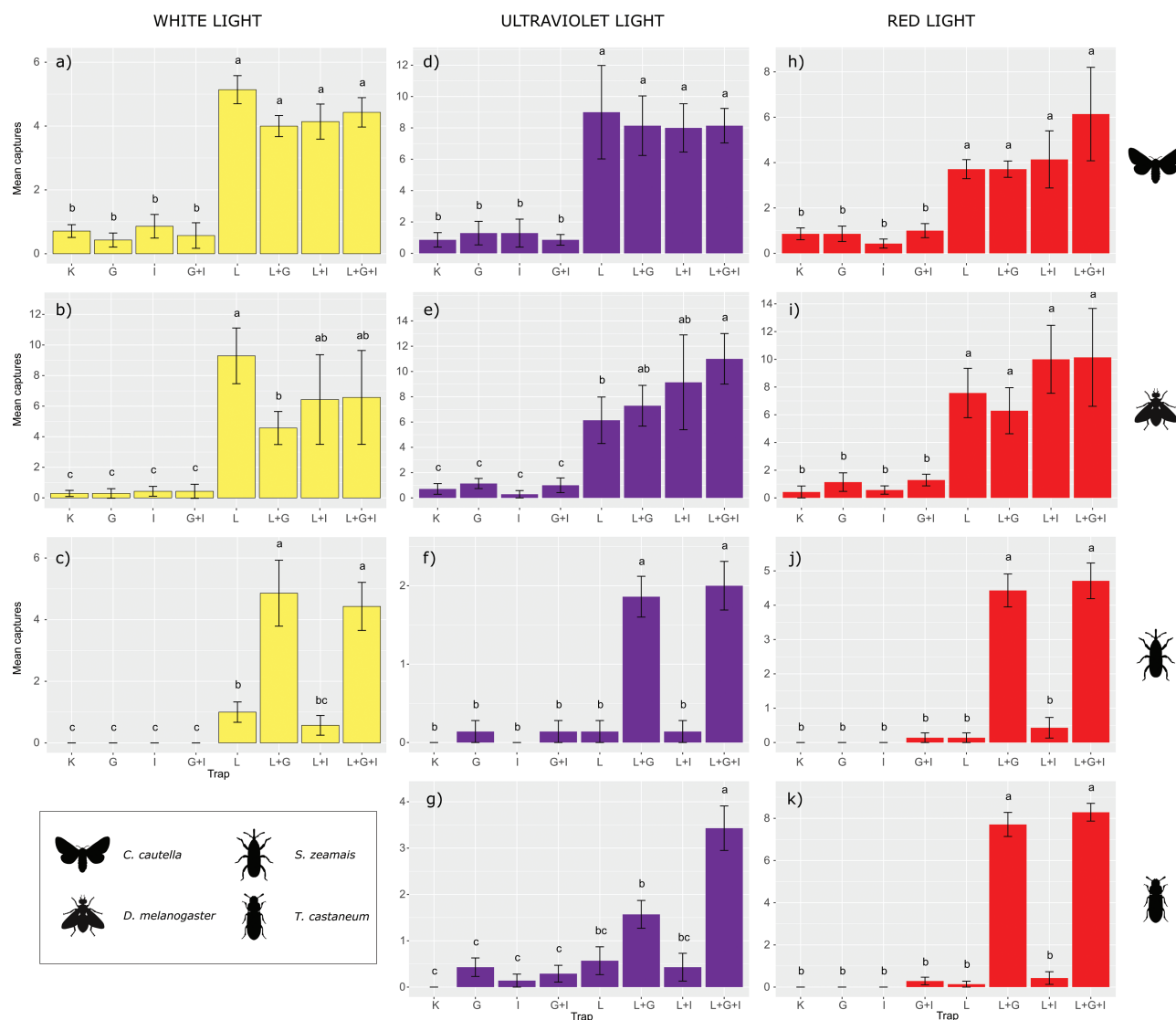


Fig. 3. Mean (\pm SE) number of insects captured by each trap combination during the 'Single color tests' and divided for each model species (rows) and light color (columns). Means with different letters on the same graph were significantly different.

individual of *T. castaneum* was captured in traps L and L + G + I, and numbers too low to allow statistical analysis.

Single Color Test—Infrared Light

The four model species were captured only in very low numbers in traps activated with infrared light. Although for beetles (*S. zeamais* and *T. castaneum*) there were a few captures in traps treated with additional glue or insecticide (G, G + I, L + G, L + I, and L + G + I), there were no significant differences between the eight tested trap models (Supp Tables S2 and S3 [online only]).

Single Color Test—Ultraviolet Light

Similar to the white light test, *C. cautella* and *D. melanogaster* were caught significantly more by light-on traps (L, L + G, L + I, and L + G + I) than light-off traps (Table 1; Supp Table S2 [online only]; Fig. 3d). In addition, for *D. melanogaster*, L + G + I captured significantly more individuals than L traps (Table 1; Supp Table S2 [online only]; Fig. 3e). With beetles (*S. zeamais* and *T. castaneum*), L + G and L + G + I captured significantly more insects than the other trap models (Table 1). Although for *S. zeamais* the other six trap models showed no significant differences (with C and I trapping no

individuals [Supp Table S3 [online only]; Fig. 3f]), for *T. castaneum* L + G + I was the trap type that captured the largest number of insects, whereas L + G captured significantly more than C, G, I, and G + I traps (Supp Table S3 [online only]; Fig. 3g).

Single Color Test—Red Light

Again, *C. cautella* and *D. melanogaster* were captured significantly more by light-on (L, L + G, L + I, and L + G + I) than light-off traps (Table 1; Supp Table S2 [online only]; Fig. 3h–i). Similarly, light-on traps coated with additional glue (L + G and L + G + I) caught significantly more individuals of *S. zeamais* ($P < 0.001$, $K = 46.290$) and *T. castaneum* ($P < 0.001$, $K = 45.231$); in both beetle species, C, G, and I traps captured no insects (Supp Table S3 [online only]; Fig. 3j–k).

Multicolor Tests

Captures of *C. cautella* in ultraviolet light trap were significantly higher than in control (light-off trap) and infrared light traps, but without differences from white and red light traps (Table 1; Supp Table S2 [online only]; Fig. 4a). For *D. melanogaster* white, ultraviolet and red light traps caught a significantly higher number of

individuals than control and infrared light traps. Moreover, white and ultraviolet light traps captured more than the red one (Table 1; Supp Table S2 [online only]; Fig. 4b). Lastly, for *S. zeamais* and *T. castaneum*, red light trap outperformed the others. Ultraviolet and white light traps caught significantly more individuals of *S. zeamais* than control and infrared light traps (Table 1; Supp Table S2 [online only]; Fig. 4c), whereas for *T. castaneum*, ultraviolet light trap outperformed control, infrared, and white traps (Table 1; Supp Table S2 [online only]; Fig. 4d).

Discussion

Results show different phototactic responses for the various tested species. All model species showed a general attraction to light: in fact, in all the single color tests (except for infrared light) light-on traps captured more specimens. Only *T. castaneum* did not present an attraction for white light. In particular, in the multi-color test, we found that *C. cautella* has no preference between white, ultraviolet, and red lights; *Drosophila melanogaster* prefers ultraviolet and white over red light; *Sitophilus zeamais* and *T. castaneum* have a much greater attraction to red light.

Land (1997) observed that, in general, insects can perceive light ranging in wavelength from 350 (ultraviolet) to 700 nm (red) and

results of the ‘single-color tests’ agree with him. In fact, for all four model species, we obtained a significant effect of light with ultraviolet, white, and red wavelengths, but not with infrared (940 nm). Moreover, light-on traps (with white, ultraviolet, and red LED) with the addition of entomological glue captured significantly more beetles (both *S. zeamais* and *T. castaneum*) than normal traps or traps with insecticide only. This result confirms the hypothesis formulated by Marchioro *et al.* (2020) according to which the standard glue of sticky cards, alone, was unsuitable to retain trapped beetles. Adding insecticide does not improve trap performance, probably because beetles are able to escape before dying. This is also true for Lepidoptera and Diptera: in fact, captures of light-on traps with insecticide are similar to other light-on traps. However, avoiding the use of insecticides may also allow trap use in containers transporting food, without risk of goods contamination.

White light shows among the best results for catching Lepidoptera and Diptera (although with no significant differences from ultraviolet and red light), probably due to its composition of two peaks at indigo and green-yellow wavelength. Measures of spectral efficiency of *C. cautella*, in fact, highlight two regions of high efficiency at 546 nm (yellow-green) and 350 nm (ultraviolet) (Gilbert and Anderson 1996). Moreover, it has been observed by numerous studies that green and blue lights are very effective in

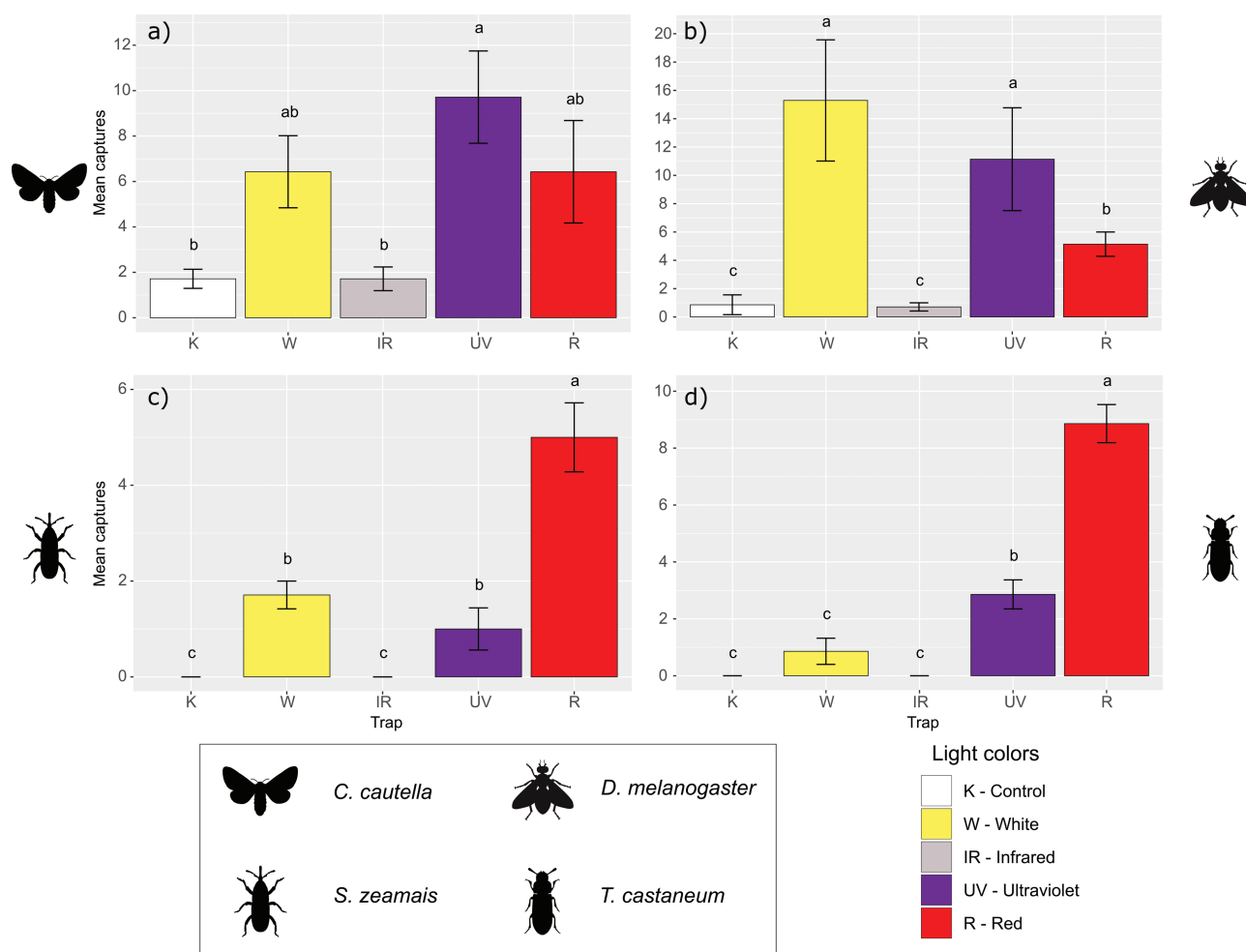


Fig. 4. Mean (\pm SE) number of insects, divided for each model species, captured by each light color during the ‘Multi-color test’. Means with different letters on the same graph were significantly different.

catching many Lepidoptera, like for instance *Ephesia kuehniella* (Soderstrom 1970), *Plodia interpunctella* (Soderstrom 1970, Park and Lee 2016), *Sitotroga cerealella* (Soderstrom 1970), *Spodoptera exigua* (Oh 2011), *Spodoptera litura* (Yang et al. 2012), and *Plutella xylostella* (Cho and Lee 2012). Also *D. melanogaster* is most sensitive to short wavelength lights (ultraviolet, blue, and green) with two peaks at 420 nm and 495 nm (de Salomon and Spatz 1983, Kelber and Henze 2013). Light traps with similar wavelengths are largely used for moth monitoring, but they may also intercept Diptera (Kim and Lee 2014a, da Silva et al. 2019, Ndengué et al. 2019, Silva et al. 2019).

Ultraviolet was one of the best wavelengths for Lepidoptera and Diptera (although catches did not differ from those obtained with white and red light), while it provided scarce results for Coleoptera. The general effectiveness of UV as an attraction for several insects is well-known (Hollingsworth et al. 1968, Kirkpatrick et al. 1970, van Grunsven et al. 2014, Thein and Choi 2016), in particular, for moths (Cho and Lee 2012, Infusino et al. 2017) and flies (Gaglio et al. 2018, Hogsette 2019). Regarding *S. zeamais* and *T. castaneum*, the literature instead provides conflicting results about the attractiveness of UV. On one hand, Duehl et al. (2011) found that *T. castaneum* was most attracted by UV wavelength and Kirkpatrick et al. (1970) found that some species of stored-products beetles preferred UV over green light. On the other hand, Park et al. (2015) and Song et al. (2016a) found that UV light was the less attractive for *S. zeamais* and *T. castaneum*.

Red wavelength also showed high attractiveness for our model species. For *C. cautella*, the number of trapped insects was similar to white and ultraviolet lights, as found for the similar species *P. interpunctella* (Park and Lee 2016). However, for other moth species belonging to different orders, results are different: red light is less attractive than other light colors in *S. litura* (trapped with blue and green [Yang et al. 2012]), *S. exigua* (trapped with white light [Oh 2011]), and *S. cerealella* (trapped with ultraviolet light [Kim and Lee 2014b]). For *D. melanogaster* captures obtained with red light were lower than white and ultraviolet lights. Also for another Dipteran, *Liriomyza trifolii*, red light was less attractive than green and yellow lights, but more attractive than ultraviolet (Kim and Lee 2014a). Finally, for both beetle species, red light was the most attractive one, with more than twice the catches than those of white and ultraviolet. These results agree with other researches conducted on the phototactic behaviour of *S. zeamais* (Park et al. 2015) and *T. castaneum* (Song et al. 2016a, 2016b), where red light was the best wavelength for both species. However, different results were obtained for other beetles: *S. oryzae*, congeneric of *S. zeamais*, preferred blue and green lights, whereas red and ultraviolet lights showed similarly lower capture performance (Jeon et al. 2012).

Finally, in our trials, infrared light was not attractive to any of the tested species. This result is not surprising as insect vision is generally shifted towards ultraviolet and they seem unable to see infrared radiation (Land, 1997). Other studies dealing with the phototactic behaviour of fly and moth species confirm this observation (Cho and Lee 2012, Kim and Lee 2014a, 2014b, Park and Lee 2016). However, certain studies have shown a similar attraction of *S. zeamais* to red, yellow, and infrared light (Park et al. 2015), and of *T. castaneum* similar to infrared, white, yellow, green, and blue lights, and higher than ultraviolet (Song et al. 2016a).

In conclusion, we found that light is an effective ‘broad-spectrum’ attractant for several insect species belonging to different orders. Moreover, the use of a stronger glue on the sticky cards improves captures of beetles (although it does not improve moth and fly catches), solving the problem highlighted by Marchioro et al. (2020).

Instead, the insecticide, in the formulations and doses tested, does not give any improvement in terms of catches. However, we also found that there is a clear response of the different species to the different lights tested: white and ultraviolet lights are the most attractive for *C. cautella* and *D. melanogaster*, while red is the most effective in catching beetles. Moreover, we can hypothesize that using at the same time different traps with different light colors, there must have been some interference in the case of two colors both attractive to one species. Probably, using only one trap, the trap performance will increase. A possible solution could consist in the use of different lights at the same time in the same trap, but further studies should verify that this combination can improve the trap performance and is not a repellent. The aim of this study is to find a trap that can be used in a wide range of shipments, with a wide variety of commodities. The tested glue (Temo-O-Cid) is non-toxic and this allows the trap to be used in conjunction with any type of food product (grains, flours, fruits, and vegetables). However, it can be used with any kind of cargo that can carry hitchhikers’ insects. This is only a pilot study that used few model species. In order to obtain more comprehensive and reliable results, other tests must be conducted, possibly during real shipments.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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References Cited

- Aldawood, A. S., K. G. Rasool, A. H. Alrukban, A. Soffan, M. Husain, K. D. Sutanto, and M. Tufail. 2013. Effects of temperature on the development of *Ephesia cautella* (Walker) (Pyralidae: Lepidoptera): a case study for its possible control under storage conditions. *Pakistan J. Zool.* 45: 1573–1578.
- Alpha Scents Inc. 2013. Yellow Rectangle Adhesive Traps. <https://www.alphascent.com/pub/media/Pdf/Flyer Yellow Cards.pdf>
- Augustin, S., N. Boonham, W. J. De Kogel, P. Donner, M. Faccoli, D. C. Lees, L. Marini, N. Mori, E. Petrucco Toffolo, S. Quilici, et al. 2012. A review of pest surveillance techniques for detecting quarantine pests in Europe. *EPPO Bull.* 42: 515–551.
- Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67: 1–51.
- Bernhofen, D. M., Z. El-Sahli, and R. Kneller. 2016. Estimating the effects of the container revolution on world trade. *J. Int. Econ.* 98: 36–50.
- Bertelsmeier, C., S. Ollier, A. Liebhold, and L. Keller. 2017. Recent human history governs global ant invasion dynamics. *Nat. Ecol. Evol.* 1: 1–17.
- Birmingham, A. L., E. Kovacs, J. P. Lafontaine, N. Avelino, J. H. Borden, I. S. Andreller, and G. Gries. 2011. A new trap and lure for *Drosophila melanogaster* (Diptera: Drosophilidae). *J. Econ. Entomol.* 104: 1018–1023.
- Bogich, T. L., A. M. Liebhold, and K. Shea. 2008. To sample or eradicate? A cost minimization model for monitoring and managing an invasive species. *J. Appl. Ecol.* 45: 1134–1142.

- Bradshaw, C. J., B. Leroy, C. Bellard, D. Roiz, C. Albert, A. Fournier, M. Barbet-Massin, J. M. Salles, F. Simard, and F. Courchamp. 2016. Massive yet grossly underestimated global costs of invasive insects. *Nat. Commun.* 7: 12986.
- Brown, S. J., T. D. Shippy, S. Miller, R. Bolognesi, R. W. Beeman, M. D. Lorenzen, G. Bucher, E. A. Wimmer, and M. Klingler. 2009. The red flour beetle, *Tribolium castaneum* (Coleoptera): a model for studies of development and pest biology. *Cold Spring Harb. Protoc.* 4: 1–9.
- Bullock, J. M., D. Bonte, G. Pufal, C. da Silva Carvalho, D. S. Chapman, C. García, D. García, E. Matthysen, and M. M. Delgado. 2018. Human-mediated dispersal and the rewiring of spatial networks. *Trends Ecol. Evol.* 33: 958–970.
- Cho, K.-S., and H.-S. Lee. 2012. Visual preference of diamondback moth, *Plutella xylostella*, to light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* 55: 681–684.
- Cohnstaedt, L. W., J. I. Gillen, and L. E. Munstermann. 2008. Light-emitting diode technology improves insect trapping. *J. Am. Mosq. Control Assoc.* 24: 331–334.
- Danho, M., C. Gaspar, and E. Haubruge. 2002. The impact of grain quantity on the biology of *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae): oviposition, distribution of eggs, adult emergence, body weight and sex ratio. *J. Stored Prod. Res.* 38: 259–266.
- Duehl, A. J., L. W. Cohnstaedt, R. T. Arbogast, and P. E. Teal. 2011. Evaluating light attraction to increase trap efficiency for *Tribolium castaneum* (Coleoptera: Tenebrionidae). *J. Econ. Entomol.* 104: 1430–1435.
- Englert, D. C., and A. E. Bell. 1962. Sex ratio in *Tribolium castaneum* Herbst as influenced by larval starvation. *Oikos*. 13: 118–124.
- Erenso, T. F., and D. H. Berhe. 2016. Effect of neem leaf and seed powders against adult maize weevil (*Sitophilus zeamais* Motschulsky) mortality. *Int. J. Agric. Res.* 11: 90–94.
- Everett, R. A. 2000. Patterns and pathways of biological invasions. *Trends Ecol. Evol.* 15: 177–178.
- Gaglio, G., E. Napoli, F. Arfuso, J. M. Abbate, S. Giannetto, and E. Brianti. 2018. Do different LED colours influence sand fly collection by light trap in the Mediterranean? *Biomed Res. Int.* 2018: 6432637.
- Garstang, R. H. 2004. Mount Wilson observatory: the sad story of light pollution. *The Observatory* 124: 14–21.
- Gilburt, H. L., and M. Anderson. 1996. The spectral efficiency of the eye of *Ephesia cautella* (Walker) (Lepidoptera: Pyralidae). *J. Stored Prod. Res.* 32: 285–291.
- van Grunsven, R. H. A., M. Donners, K. Boeke, I. Tichelaar, K. G. van Geffen, D. Groenendijk, F. Berendse, and E. M. Veenendaal. 2014. Spectral composition of light sources and insect phototaxis, with an evaluation of existing spectral response models. *J. Insect Conserv.* 18: 225–231.
- Hogsette, J. A. 2019. Turning ultraviolet light traps on and off increases their attraction to house flies (Diptera: Muscidae). *J. Insect Sci.* 19: 22–23.
- Hollingsworth, J. P., A. W. Hartstack, and D. A. Lindquist. 1968. Influence of near-ultraviolet output of attractant lamps on catches of insects by light traps. *J. Econ. Entomol.* 61: 515–521.
- Hulme, P. E. 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. *J. Appl. Ecol.* 46: 10–18.
- Hulme, P. E. 2014. An introduction to plant biosecurity: past, present and future, pp. 1–25. In G. Gordh and S. McKirdy (eds.), *The handbook of plant biosecurity*. Springer Netherlands, Dordrecht.
- Hulme, P. E., S. Bacher, M. Kenis, S. Klotz, I. Kühn, D. Minchin, W. Nentwig, S. Olenin, V. Panov, J. Pergl, et al. 2008. Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *J. Appl. Ecol.* 45: 403–414.
- Hulme, P. E., P. Pyšek, W. Nentwig, and M. Vilà. 2009. Will threat of biological invasions unite the European Union? *Science*. 324: 40–41.
- Husain, M., W. S. Alwaneen, K. Mehmood, K. G. Rasool, M. Tufail, and A. S. Aldawood. 2017. Biological traits of *Cadra cautella* (Lepidoptera: Pyralidae) reared on Khodari date fruits under different temperature regimes. *J. Econ. Entomol.* 110: 1923–1928.
- Infusino, M., G. Brehm, C. Di Marco, and S. Scalercio. 2017. Assessing the efficiency of UV LEDs as light sources for sampling the diversity of macro-moths (Lepidoptera). *Eur. J. Entomol.* 114: 25–33.
- International Maritime Organization (IMO). 2012. International shipping facts and figures information resources on trade, safety, security, environment. IMO, London, UK.
- International Organization for Standardization (ISO). 2013. TC 104. ISO 668: 2013. Series 1 freight containers-classification, dimensions and ratings. Int. Organ. Stand., Geneva, Switz.
- Jeon, J.-H., M.-S. Oh, K.-S. Cho, and H.-S. Lee. 2012. Phototactic response of the rice weevil, *Sitophilus oryzae* Linnaeus (Coleoptera: Curculionidae), to light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* 55: 35–39.
- Kelber, A., and M. J. Henze. 2013. Colour vision: parallel pathways intersect in *Drosophila*. *Curr. Biol.* 23: R1043–R1045.
- Kim, M.-G., and H.-S. Lee. 2014a. Attractive effects of american serpentine leafminer, *Liriomyza trifolii* (Burgess), to light-emitting diodes. *J. Insect Behav.* 27: 127–132.
- Kim, M.-G., and H.-S. Lee. 2014b. Phototactic behavior 5: attractive effects of the angoumois grain moth, *Sitotroga cerealella*, to light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* 57: 259–262.
- Kirkpatrick, R. L., D. L. Yancey, and F. O. Marzke. 1970. Effectiveness of green and ultraviolet light in attracting stored-product insects to traps. *J. Econ. Entomol.* 63: 1853–1855.
- Land, M. F. 1997. Visual acuity in insects. *Annu. Rev. Entomol.* 42: 147–177.
- Levine, J. M., and C. M. D'Antonio. 2003. Forecasting biological invasions with increasing international trade. *Conserv. Biol.* 17: 322–326.
- Liebholt, A. M., and P. C. Tobin. 2008. Population ecology of insect invasions and their management. *Annu. Rev. Entomol.* 53: 387–408.
- Mallis, A. 1954. *Handbook of Pest Control*. The behavior, life history, and control of household pests, 2nd ed. MacNair-Dorland Co., New York, N.Y.
- Mangan, R. L., and D. Chapa. 2013. Evaluation of the effects of light source and plant materials on asian citrus psyllid (Hemiptera: Psyllidae) trapping levels in the transtrap for citrus shipping containers. *Florida Entomol.* 96: 104–111.
- Marchioro, M., A. Battisti, and M. Faccoli. 2020. Light Traps in Shipping Containers: A New Tool for the Early Detection of Insect Alien Species. *J. Econ. Entomol.* 113: 1718–1724.
- Meurisse, N., D. Rassati, B. P. Hurley, E. G. Brockerhoff, and R. A. Haack. 2019. Common pathways by which non-native forest insects move internationally and domestically. *J. Pest Sci.* 92: 13–27.
- National Research Council (NRC). 2002. *Predicting invasions of nonindigenous plants and plant pests*. National Academy Press, Washington, DC.
- Ndengué, J. D. M., G. Texier, J. Landier, E. De Gavelle, J. Marchi, L. R. Kamgang, M. Kenné, M. Tindo, S. Eyangoh, and P. Le Gall. 2019. Adapting light trap to catch household insects in central Cameroon: a pilot study. *Ann. la Société Entomol. Fr.* 55: 383–394.
- Nwosu, L. C. 2018. Impact of age on the biological activities of *Sitophilus zeamais* (Coleoptera: Curculionidae) adults on stored maize: implications for food security and pest management. *J. Econ. Entomol.* 111: 2454–2460.
- Oh, M. S. 2011. Evaluation of high power light emitting diodes (HPLEDs) as potential attractants for adult *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae). *J. Korean Soc. Appl. Biol. Chem.* 54: 416–422.
- Olenici, N., A. Roques, and V. Olenici. 2001. Effectiveness of visual traps for detection and survey of cone flies, *Strobilomyia* spp. (Diptera: Anthomyiidae), infesting cones of European larch (*Larix decidua* Mill.) in Romania, pp. 100–104. In: M. Knizek, B. Forster and W. Grodzki (eds.), *Methodology of forest insect and disease survey in Central Europe*. Proceedings of the IUFRO WP 7.03.10 Workshop, 24–28 September 2000, Busteni, Romania. Forest Research and Management Institute, Bucharest.
- Park, J.-H., and H.-S. Lee. 2016. Phototactic behavior 10: phototactic behavioral effects of *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) adults to different light-emitting diodes of seven wavelengths. *J. Appl. Biol. Chem.* 59: 95–98.
- Park, J.-H., and H.-S. Lee. 2017. Phototactic behavioral response of agricultural insects and stored-product insects to light-emitting diodes (LEDs). *Appl. Biol. Chem.* 60: 137–144.
- Park, J. H., B. K. Sung, and H. S. Lee. 2015. Phototactic behavior 7: phototactic response of the maize weevil, *Sitotroga zeamais* Motsch (Coleoptera: Curculionidae), to light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* 58: 373–376.

- Poland, T. M., and D. Rassati. 2019. Improved biosecurity surveillance of non-native forest insects: a review of current methods. *J. Pest Sci.* 92: 37–49.
- Puth, L. M., and D. M. Post. 2005. Studying invasion: have we missed the boat? *Ecol. Lett.* 8: 715–721.
- R Core Team. 2019. R version 3.6.1: A language and environment for statistical computing. R Found. Stat. Comput., Vienna, Austria. <https://www.R-project.org>.
- Rassati, D., M. Faccoli, E. Petrucco Toffolo, A. Battisti, and L. Marini. 2015. Improving the early detection of alien wood-boring beetles in ports and surrounding forests. *J. Appl. Ecol.* 52: 50–58.
- Rassati, D., L. Marini, M. Marchioro, P. Rapuzzi, G. Magnani, R. Poloni, F. Di Giovanni, P. Mayo, and J. Sweeney. 2019. Developing trapping protocols for wood-boring beetles associated with broadleaf trees. *J. Pest Sci.* 92: 267–279.
- Ricciardi, A., T. M. Blackburn, J. T. Carlton, J. T. A. Dick, P. E. Hulme, J. C. Iacarella, J. M. Jeschke, A. M. Liebhold, J. L. Lockwood, H. J. MacIsaac, *et al.* 2017. Invasion science: a horizon scan of emerging challenges and opportunities. *Trends Ecol. Evol.* 32: 464–474.
- Russell, L. 2019. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.5-1. <https://CRAN.R-project.org/package=emmeans>
- Sakalian, V., and L. Mario. 2004. Colour traps a method for distributional and ecological investigations of Buprestidae (Coleoptera). *Acta Soc. Zool. Bohem.* 68: 53–59.
- de Salomon, C. H., and H.-C. Spatz. 1983. Colour vision in *Drosophila melanogaster*: wavelength discrimination. *J. Comp. Physiol.* 150: 31–37.
- Santos, M., K. Fowler, and L. Partridge. 1994. Gene-environment interaction for body size and larvae in *Drosophila melanogaster*: an investigation of effects on development time, thorax length and adult sex ratio. *Genet. Soc. Gt. Britain.* 72: 515–521.
- Seebens, H., T. M. Blackburn, E. E. Dyer, P. Genovesi, P. E. Hulme, J. M. Jeschke, S. Pagad, P. Pyšek, M. Winter, M. Arianoutsou, *et al.* 2017. No saturation in the accumulation of alien species worldwide. *Nat. Commun.* 8: 14435.
- da Silva, A. A., J. M. M. Rebêlo, B. F. Carneiro, M. P. P. Castro, M. de Sousa de Almeida, I. S. Ponte, J. V. C. Aguiar, and F. S. Silva. 2019. Exploiting the synergistic effect of Kairomones and light-emitting diodes on the attraction of Phlebotomine sand flies to light traps in Brazil. *J. Med. Entomol.* 56: 1441–1445.
- Silva, F. S., B. M. Costa-Neta, M. de Sousa de Almeida, E. C. de Araújo, and J. V. C. Aguiar. 2019. Field performance of a low cost, simple-to-build, non-motorized light-emitting diode (LED) trap for capturing adult *Anopheles* mosquitoes (Diptera: Culicidae). *Acta Trop.* 190: 9–12.
- Soderstrom, E. L. 1970. Effectiveness of green electroluminescent lamps for attracting stored-product insects. *J. Econ. Entomol.* 63: 726–731.
- Soffan, A., Y. N. Aldryhim, and A. S. Aldawood. 2012. Effects of sex ratio and pairing duration on the biological performance of adult almond moth, *Ephestia cautella* (Walker) (Lepidoptera: Pyralidae). *J. Agric. Urban Entomol.* 28: 25–33.
- Song, J., S.-G. Lee, and H.-S. Lee. 2016a. Effect of LED trap on controlling *Sitophilus zeamais* and *Tribolium castaneum* in granary. *J. Appl. Biol. Chem.* 59: 129–132.
- Song, J., E.-Y. Jeong, and H.-S. Lee. 2016b. Phototactic behavior 9: phototactic behavioral response of *Tribolium castaneum* (Herbst) to light-emitting diodes of seven different wavelengths. *J. Appl. Biol. Chem.* 59: 99–102.
- Surkov, I. V., A. G. J. M. Oude Lansink, O. van Kooten, and W. van der Werf. 2008. A model of optimal import phytosanitary inspection under capacity constraint. *Agric. Econ.* 38: 363–373.
- Thein, P. P., and S.-W. Choi. 2016. Forest insect assemblages attracted to light trap on two high mountains (Mt. Jirisan and Mt. Hallasan) in South Korea. *J. For. Res.* 27: 1203–1210.
- Westphal, M. I., M. Browne, K. MacKinnon, and I. Noble. 2008. The link between international trade and the global distribution of invasive alien species. *Biol. Invasions.* 10: 391–398.
- Yang, J.-Y., M.-G. Kim, and H.-S. Lee. 2012. Phototactic behavior: attractive effects of *Spodoptera litura* (Lepidoptera: Noctuidae), tobacco cutworm, to high-power light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* 55: 809–811.
- Yeh, N., and J.-P. Chung. 2009. High-brightness LEDs - energy efficient lighting sources and their potential in indoor plant cultivation. *Renew. Sustain. Energy Rev.* 13: 2175–2180.