EUROPEAN JOURNAL OF ENTOMOLOGY
ISSN (online): 1802-8829
http://www.eje.cz
Eur. J. Entomol. **118**: 315–321, 2021
doi: 10.14411/eje.2021.032
ORIGINAL ARTICLE

A cheap electronic sensor automated trap for monitoring the flight activity period of moths

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Key words. Lepidoptera, Tortricidae, *Grapholita molesta*, mating disruption, flight activity, pheromone trap catches, automated electronic registration, Raspberry Pi

Abstract. Automated pheromone dispensers disrupt the mating behaviour of pest moths by releasing pheromone during their daily activity period, which is not the same for all target species. These periods usually occur in or close to night time and last just a few hours, so automated sampling devices are needed to characterize them. However, the commercially available automated models do not provide enough temporal resolution for characterizing the short diel periods of sexual activity of moths. Thus, we built and tested a relatively cheap and simple high-temporal-resolution image-sensor insect trap. It consisted of a Raspberry Pi computer with an infrared camera operated by open-source software and housed in a plastic box. The Raspberry Pi was powered by a solar panel and rechargeable battery that were mounted on a solid and weather-proof structure made of cheap materials. Pictures were downloaded by WiFi from the Raspberry's SD card to a computer. Six traps baited either with synthetic sex pheromone or with females of *Grapholita molesta* (Busk) were tested in the field. The traps were sturdy, reliable and easy to use, taking pictures at 10 min intervals, 24 h a day for over two months. These pictures confirmed previous results regarding the period of sexual activity of the oriental fruit moth, which will aid in determining the optimal time for operating automated pheromone dispensers.

INTRODUCTION

Mating disruption (MD) is a highly effective non-insecticidal method of controlling pests that reduces the probability of sexual encounters in species that rely strongly on the use of sex pheromones, such as moths (Cardé & Minks, 1995; Miller & Gut, 2015). The traditional method of MD is to manually install hundreds of passive dispensers per hectare and permeate an orchard with pheromone (Witzgall et al., 2008). This method is labour intensive and wastes costly pheromone during the period when insects are not sexually active, which is most of each day (McNeil, 1991; Groot, 2014). A more cost-effective technique consists of releasing larger quantities of pheromone from fewer point sources and only during the time that the insects are active. Such automated sprayers were developed in the 1990s and their use is gradually increasing (Benelli et al., 2019).

Although the sex pheromone of several hundred species of moths is identified (El-Sayed, 2019) and the period when females release sex pheromone (i.e., calling period) is known for several moths (mainly under laboratory conditions) (Groot, 2014; Harari et al., 2015), there are very few reports of the sexual periodicity of male moths, either in the laboratory or in the field (e.g., Batiste et al., 1973a; Rothschild & Minks, 1974; Quiring, 1994; Cardé et al., 1996; Zhang et al., 1998; Kim et al., 2011; Lucchi et al., 2018; Yang et al., 2019). One likely reason for the scarcity of such studies in the field, not only for moths but most insects, is that often the activity periods are relativity short and nocturnal. Automated methods only became available relatively recently (Manoukis & Collier, 2019; Preti et al., 2021) and therefore, the traps used in the majority of the studies on insect periodicity in the field were made by the researchers (e.g., Guarnieri et al., 2011; Kim et al., 2011; Doitsidis et al., 2017; Ünlü et al., 2019). These early traps were relatively complicated because they used mechanical methods (e.g., Batiste, 1970; Schouest & Miller, 1994; Stevenson & Harris, 2009). With the advent of cheap, small and more sophisticated and accessible electronic components and sensors, several automated traps were developed. The *image capture system* uses a camera to take pictures at regular intervals. This method allows either species to be identified manually (Guarnieri et al., 2011; Ünlü et al., 2019) or with the aid of digital-image processing (Zhao et al., 2016; Doitsidis et al., 2017). However, running such a sensor for prolonged periods of time requires a relatively high-power supply, which needs to be increased if images are sent remotely. When pictures are stored in situ it is necessary to have a high digital storage capacity. The *event sensor system* records each individual detected, either by interrupting a light beam (Kim et al., 2011; Jung et al., 2013; Goldshtein et al., 2017), or by some other device (e.g., Tobin et al., 2009). Finally, as different insects flap their wings at specific frequencies, a *wing-beat detector system* was developed to detect the approach of insects to a lure. Early devices used microphones (reviewed in Chen et al., 2014) but more recent ones use light interference detectors (Chen et al., 2014; Potamitis et al., 2014). Event sensor and wing-beat detector systems require less energy to run and memory to store information than the image sensor system, but they require learning algorithms for species identification and are likely to record the same individual many times (Chen et al., 2014).

Although commercial companies have been tracking these technical developments, there are relatively few automated moth traps on the market (e.g., Semios Technologies Inc., Vancouver, Canada; TrapView, Hruševje, Slovenia; iSCOUT, Pessl instruments, Weiz, Austria). These traps are designed to count captures remotely once or twice a day so that growers can take prompt pest management decisions in response to daily or seasonal population changes. A much higher temporal resolution is needed to determine the short diel periods of activity of most insect species. Although it is possible to increase the frequency of sampling by commercial traps (Lucchi et al., 2018) by increasing the power supply, it results in further increases in the cost of an already expensive product.

In this paper we describe a low-cost and durable image-sensor insect trap, made with accessible components that can be easily programmed using open-source software, which is capable of high temporal resolution of diurnal and nocturnal samples. To test the trap, we sampled the activity of males of the oriental fruit moth, *Grapholita molesta* (Busk) using sex pheromone and live-female baits every 10 min for over two months.

MATERIAL AND METHODS

The trap

The insect trap (from here on "trap box") consisted of two modified 2.8 L polypropylene food containers (Table 1), one of them serving as a cover for the other to protect the electronic components from adverse weather conditions (Fig. 1A). The electronic components were attached to the top of the inner plastic box. A hole drilled at its centre allowed the camera to take photographs of the sticky card lining the lid of the other lunch-box, which is the actual trap floor. The sticky card was attached to the lid with hook-and-loop fasteners for easy replacement. Holes were drilled in each corner of the floor of the lid for draining rain water. Flying males entered the trap box through 11.5-cm wide × 5-cm tall windows in the two opposing walls of the inner plastic

Table 1. Trap components.

Electronic components	
Component (Model, Brand)	Specifications
Computer board (Raspberry Pi Zero W, Raspberry Pi, UK)	Broadcom BCM2835 microprocessor, 512MB RAM, VideoCore IV, microSD
Camera (NoIR V2.1, Raspberry Pi, UK)	8 MP, Sony IMX219 sensor, focal length 3.04 mm
Infrared LED (Waveshare Electronics, China)	850 nm wavelength, photosensitive resistor
Micro SD Card (SDC4, Kingston, USA)	8GB
Camera cable (Raspberry Pi Zero, Raspberry Pi, UK)	15 × 1.6 × 0.02 cm
USB 2.0 cable (AmazonBasics, USA)	male A to micro B, 1.83 m
Heat sink (RoHS 750-0888 27K/W, ABL Components, UK)	13 × 13.5 × 10 mm, Aluminium
Power unit	
Component (Model, Brand)	Specifications
Solar panel (Enjoysolar, Germany)	20W, 51 × 30 × 2.5, 2.4 kg
Charge regulator (JZK, China)	20A, 0.195 kg
Lead Battery (10324, DSK, India)	12V 7Ah, 151 × 65 × 94 cm, 1.95 kg
Trap box	
Component (Model, Brand)	Specifications
Lunch box (GASTRONORM, GreatPlastic, Spain)	15 × 14.5 × 15 cm, 2.8 L, polypropylene
Sticky cards (Pherocon®, Trecé Incorporated)	White, 8.5 × 18.5 cm (cut to fit into the trap)
Commercial pheromone lure (Red rubber septum, Pherocon® OFM, Lot Number: 84350758, Trecé Incorporated, USA)	186 µg of *Z*8-12:Ac and 11.8 µg of *E*8-12:Ac
Software	
Software	Version
Operating system (Linux)	Raspbian GNU/Linux NOOBS 2.3
Image acquisition (Python)	Python 2.7.13
Remote access (RealVNC, Cambridge)	VNC Viewer/VNC Server 6.7.2 (Linux)
Video streaming (VLC, VideoLAN)	3.0.11 Vetinari

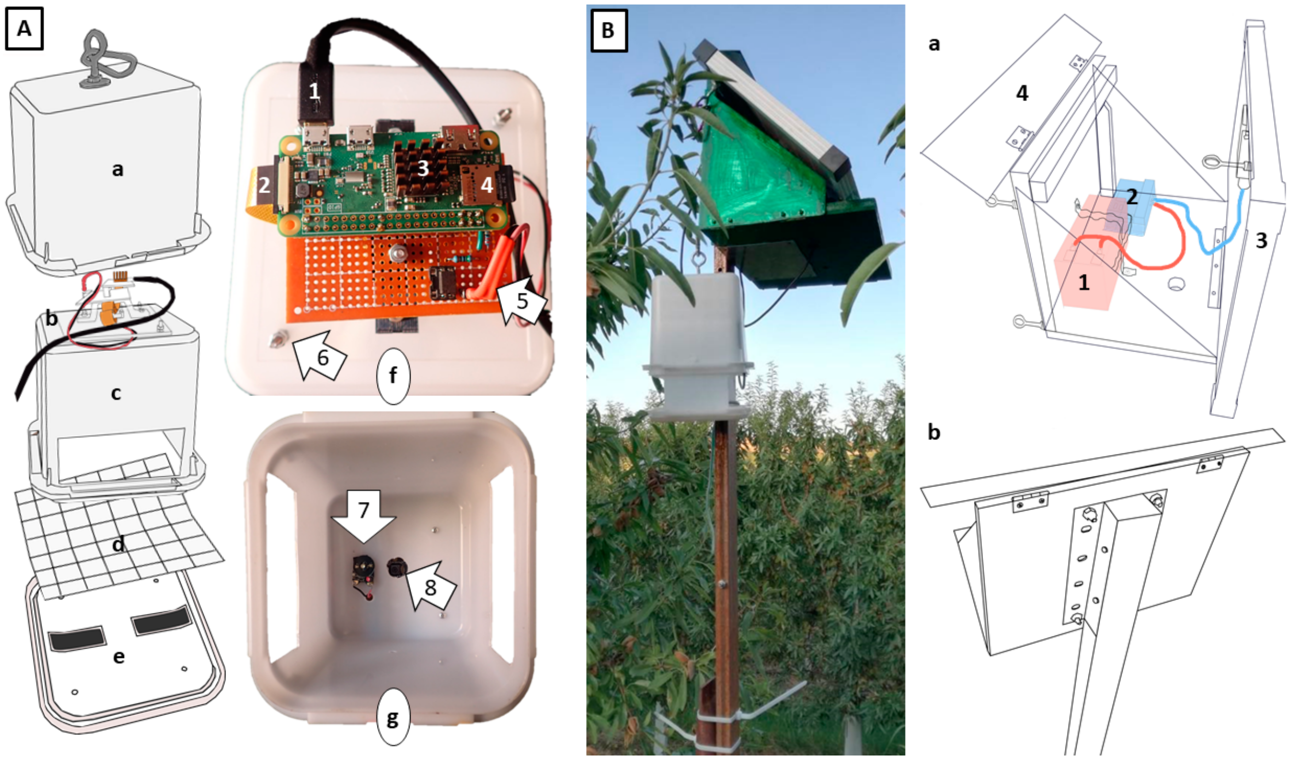

Fig. 1. Trap box and diagrams of power supply. The trap-box (A) consists of an outer plastic box (a) that slides over an inner one (c) to protect the electronic components (b and f) from weather. The lid of the bottom plastic box (e) is lined with a sticky card (d) attached by hook-and-loop fasteners for easy replacement. Close-up of the electronic components (f), showing the charge port (1), camera cable (2), heat disperser (3), micro-SD card (4) and infrared LED and connector (5). The camera´s angle can be tilted by adjusting the screws of the plastic plate on which it is mounted (6). Trap viewed from the bottom (g) showing the infrared LED (7) placed near the IR camera (8). The power supply unit (B) consists of a wooden and aluminium structure (a) and a metal post to hold the system in place (b and picture on the left). This structure holds a battery (1), a charge controller (2) and the solar panel (3). A lid made from a sheet of metal (4) provides further protection of the electronic components from weather.

box. The top box slides over the bottom one and they are fixed to each other by screws.

Power supply was provided by a solar panel, lead-acid battery and charge controller (Table 1, Fig. 1B). A structure made from wood and aluminium planks (35.5-cm wide × 27-cm deep × 25-cm tall) housed the battery and the charge controller, and protected them from weather (Fig. 1B). The solar panel roofed the structure and hinged on the wooden frame for easy access to the battery and charge controller. An extra metal plate on top provided further weather proofing. The power-supply unit was relatively heavy (frame = 3.47 kg, solar panel + battery = 4 kg) and was attached to a galvanized steel bar which had to be stiff in order to hold that weight (4.5 × 2.5-cm cross section, 150-cm long, 2.43 kg). Therefore, the final weight of the solar unit plus the metal bar is 9.9 kg. Solar unit and metal bar were assembled on site with two 8-mm diameter × 90-mm long bolts with wing nuts for hand tightening.

The electronic components of the trap consisted of a Raspberry Pi Zero Wifi computer board connected to an infrared camera (Raspberry Pi Camera NoIR v.2.1) and an infrared LED light for night vision (Fig. 2; Table 1). The infrared LED was equipped with a photoresistor to turn it on and off at user-defined ambient light levels. A heat sink attached to the Raspberry Pi CPU prevented overheating. The operating system (GNU/Linux, Full NOOBS 2.3) was installed on a micro SD card and image acquisition was configured (camera resolution 1500 × 1500 pixels) with script written in Python 2.7 code. The photographs were stored on the same micro SD card. Initial installation and configuration of the operating system required a USB mouse, USB keyboard and HDMI display. Afterwards, communication with the Raspberry board for programming and picture download was by means of Wi-Fi with a computer using a VNC server (RealVNC for Linux 6.7.2 was installed in the Raspberry computer). Detailed setup instructions are provided (Supplementary file 1).

The height at which the plastic box is located is critical because it determines the camera's field of view. If too short, then the camera photographs only a portion of the sticky card and captures outside of this area are missed. If too high then the area surrounding the sticky card is also included in the photograph and the resolution of the target image decreased. The angle of the axis of the camera's lens to the object is also decisive as its adjustment allowed the photographing of most of the sticky card. To this end, the camera was mounted on a plastic platform that allowed coarse adjustment using three screws (Fig. 1A). Focus was adjusted manually. The open-source video software VLC media player v. 3.0.12 enabled video streaming to perform these adjustments (Supplementary file 1).

The IR LED was attached to the top of the trap box, beside the camera opening, (Fig. 1A). A 1.5-m-long USB cable connected the Raspberry Pi to the power source (5VDC) provided by the charge controller. The roof of the outer plastic box was fitted with an eye bolt screw to hang the trap box with a carabineer shackle from another eye bolt screwed on the power supply structure, or elsewhere (Fig. 1). The trap box was tied to the post to prevent it from swinging in the wind (Fig. 3E).

Field tests

Males were lured to traps loaded with either sex pheromone or live females. The synthetic pheromone was a commercial lure

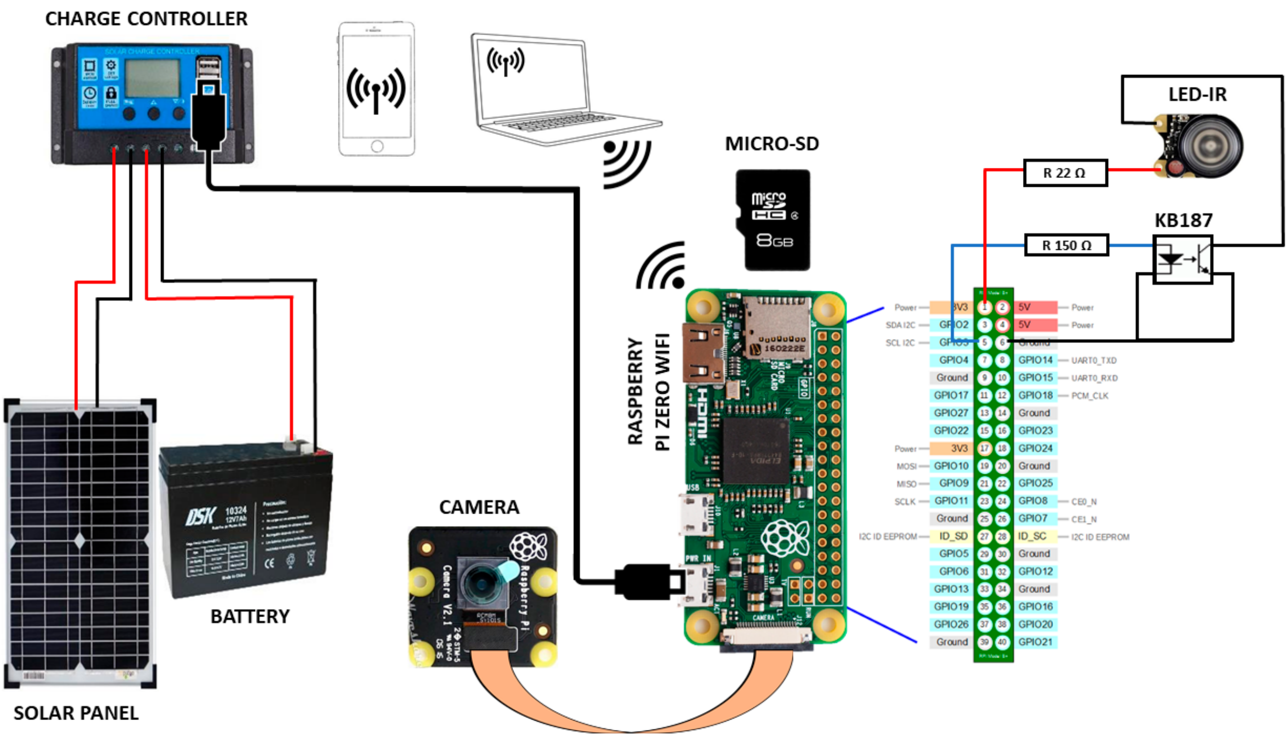

Fig. 2. Schematic representation of the electronic components of the Raspberry-Pi automated trap. Cable connections are represented by lines, and wireless connections are represented by Wi-Fi symbols. KB187 refers to the solid-state relay that switches on the LED when ambient light goes below a user-determined level.

to monitor adult populations of *G. molesta* (Pherocon® OFM, Lot Number: 84350758, Trecé Incorporated, Adair, Oklahoma, USA). It consisted of a red-rubber septum loaded with the two main pheromone ingredients of *G. molesta* (186 µg of *Z*8-12:Ac and 11.8 µg of *E*8-12:Ac; CAS # 28079-04-1 and 38363-29-0, respectively). Females were reared in the laboratory as previously described (Navarro-Roldán & Gemeno, 2017). Female pupae were placed outdoors on a window sill protected from direct sun and rain and were provided with 10% sugar water drinkers. Emerged females were collected every 1–5 days and placed in groups of 4 in wire cages made from one half of a 0.5-mm mesh screen spherical tea strainer, 3.5-cm diameter × 1.8-cm high. The wire cage was fixed with double-sided tape to the bottom of a 5.5-cm diameter plastic Petri dish. A 0.5-mL Eppendorf tube filled with 10% sugar water and fitted with a cotton plug served as a drinker (Fig. 3E). Wire cages were placed directly in the centre of the sticky card by the side of the Petri dish (Fig. 3E).

The field experiment was carried out between August 15th and October 4th, 2019 at two different locations in Lleida, Spain. At one location there was a wild population of *G. molesta*, at the other laboratory reared males were released. The first location was a 10-year-old almond orchard (41.675181N, 0.509680E, datum WGS84) with 4-m-tall trees on a trellis 1.6 m apart from each other with a distance between rows of 3.5 m. The orchard was not sprayed with insecticides against *G. molesta* but MD was used against *Anarsia lineatella* Zeller. Six traps were fixed to the metal posts of the trellis, with the solar panels placed just above the canopies of the trees (approximately 3 m high) and at least 30 m from each other. Trap boxes hung from the power supply units between 1.7 and 2.2 m from the ground. In the first period sampled (August 15th to September 9th) the traps were baited with sex pheromone. In the second (September 23rd to October 4th) two traps were baited with sex pheromone and four were baited with live females.

The second field site (41.613529N, 0.566422E, datum WGS84) was a backyard located amidst commercial apple and pear orchards and with small *G. molesta* populations. The metal bar holding the power-supply was placed directly on the ground and tied to a wooden fence post. Trap boxes hung from the power supply were set 1.2 m above the ground. Six traps were placed 8 m apart from each other forming a circle. Male pupae from the laboratory colony were placed in ventilated 600-ml plastic boxes provided with a 1.5 mL Eppendorf drinker and taken to the field. They were placed inside a 50-cm-tall shed made of loose bricks to shelter them from the sun and prevent desiccation. The shed was placed at the centre of the circle of traps. The male cage was placed inside a wire cage which hung from a wire in the shed to prevent predation (mainly from ants) while allowing free exit of adult males. New male pupae were supplied each week (approx. 50–100 at each visit). Four traps were baited with virgin females and two with synthetic pheromone and the test ran from September 12th to 24th.

Traps were visited every 3–4 days to download pictures from the Raspberry Pi computer, free up micro SD card space, replace females, and change sticky cards as needed. When only synthetic pheromone was tested, visits were made every 10 days. Captures were scored manually, image by image. Occasionally individuals changed position on the sticky card, which we could track in the majority of cases (Fig. 3). Species identity was confirmed by dissecting KOH-digested genitalia of 30 randomly selected individuals from the two field sites (Dickler, 1991) (Fig. 3D). Data on daily sunset times was provided by Time and Date AS (Stavenger, Norway, https://www.timeanddate.com/sun/).

RESULTS AND DISCUSSION

A total of 568 males were captured during the course of the experiment, on average 11.3 per trap per week, which is within the range of what is normally captured by conven-

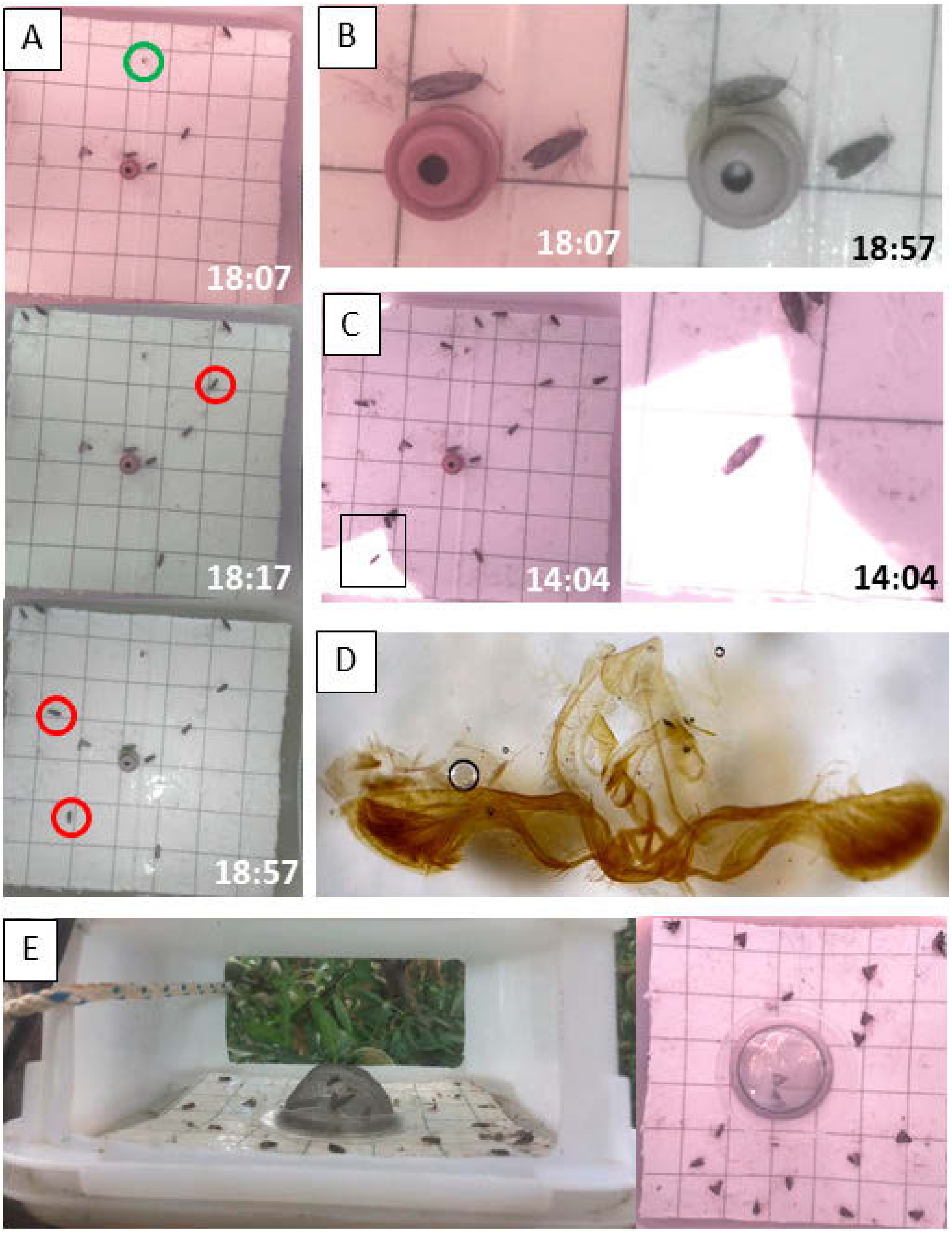

Fig. 3. A – Three consecutive photographs taken by the IR camera, the first two were taken before the IR LED was switched on, and the last one shows the reflection of the IR LED on the sticky card. B – Close-up of the first and last photographs from A to illustrate image resolution during the day (left) and at night when the IR LED light is on (right). C – Effect of direct sunlight and shade on the resolution of the moths in pictures of the sticky card. The image on the right is a close-up of a square on the left of the image. D – Dissected genitalia of one of the captured males of *G. molesta*. E – Left: Outside view of a trap box baited with live females. Right: Raspberry Pi camera photographs of females in the wire cage and males entrapped on the sticky card.

tional delta traps (Kovanci & Walgenbach, 2005; Knight et al., 2014; Özpinar et al., 2014; Kutinkova et al., 2018). Daily captures of male *G. molesta* were similar for wild and laboratory-reared males and synthetic pheromone and calling females, and clustered in a period between 2 to 3 hours before sunset (i.e., civil twilight) (Fig. 4), which is similar to that reported in previous studies in Australia, USA and Korea (Rothschild & Minks, 1974; Gentry et al., 1975; Kim et al., 2011). Thus, our traps behave similar to standard Delta traps, but a side-by-side comparison of both types of traps is needed.

The aim of this study was to build and test a high time resolution durable and affordable automated trap in order to determine daily activity periods of insects throughout the season for the optimization of an automatic MD pheromone dispenser. At a price of around 150 euros our traps are affordable, accessible and operate uninterruptedly for long periods. In view of the results, we believe this trap to be a tool of interest for research, especially because it has a higher time resolution than that of commercial traps. Here we discuss its strengths and limitations and provide suggestions for improving the latter.

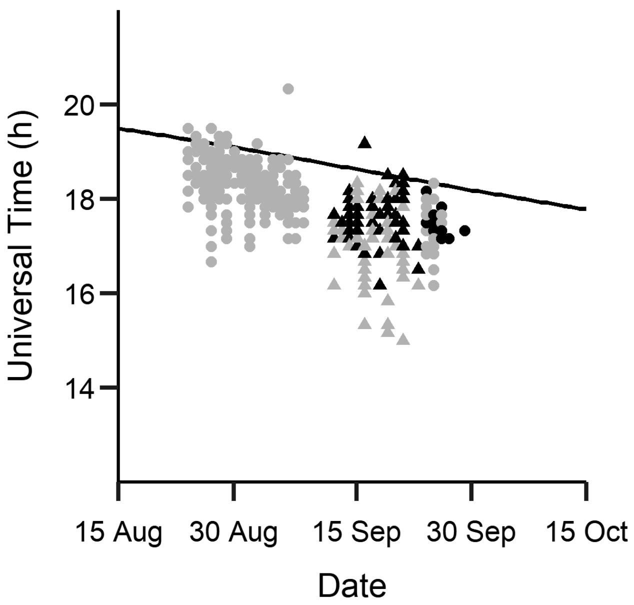

Fig. 4. Daily captures of male *G. molesta* between August 15th and October 4th 2019 relative to the time of sunset (i.e., civil twilight, solid line). Traps were baited with either live females or synthetic sex pheromone (grey and black, respectively) and males were either wild or from a laboratory colony (circles and triangles, respectively).

Our traps recorded insect activity every 10 min for over 2 months. The southward orientation of the solar panel, which was not obstructed by leaves and branches, provided a good level of charge, which is essential for prolonging battery life. Placing the traps in the field can be easily achieved by one person when they are set in the ground (as at the second field site), but it requires two people to place the 10 kg power supply units high in the canopy of a tree (as at the first field site). Future designs should consider making the traps more manageable, for example by separating the heavier power supply components (solar panel and battery).

Once installed, the traps resisted standard weather, including relatively heavy rain and strong wind. After completing the tests, nonetheless, we noticed that the plastic boxes had degraded in various places, making some of them non-reusable. We attribute this degradation to the susceptibility of the polypropylene food containers to UV radiation. Although plastic boxes are cheap, it is not practical to make new trap boxes each time they are degraded because reinstalling the electronic components and adjusting the camera position is time consuming. Using UV-resistant plastic or painting the boxes with UV-resistant paint could prolong the longevity of the trap boxes.

After the initial configuration of the Raspberry Pi, wireless connection between the trap and a computer is possible using a Wi-Fi hotspot generated by a smart phone (Fig. 2, Supplementary file 1). After one week of taking photographs at 10 min intervals the micro SD memory cards were almost full and as a consequence the traps were visited at a maximum of every 10 days to download and delete the pictures to liberate card space. A larger capacity SD card would lengthen download time, which took 10–20 min for 1-week of taking photographs at 10-min intervals. To avoid these lengthy downloading periods in the field, traps could have a General Packet Radio Service (GPRS) connection, which would make them accessible via the internet from any computer, but this would increase the cost. Moreover, visits are still needed to change the sticky cards, especially during population peaks. On the other hand, the traps could easily take 2 pictures a day for over a year without needing to download the pictures, making them a useful seasonal monitoring tool. The Raspberry Pi can be fitted with sensors that provide useful meteorological information for a minor cost and without significantly compromising card space, which would make this trap a highly competitive monitoring system.

ACKNOWLEDGEMENTS. A. Pérez-Aparicio was supported by a pre-doctoral JADE scholarship from the University of Lleida. C. Gemeno was supported by grant AGL2016-77373-C2-2-R (MEYC, Spain) and J. Llorens by a postdoctoral position at the University of Lleida. We are thankful to Vallfonda (Raimat SL) for allowing us to use the almond orchard.

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Received May 28, 2021; revised and accepted September 9, 2021
Published online October 11, 2021

Online supplementary file:
S1 (http://www.eje.cz/2021/032/S01.pdf).