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PRACTICAL TOOLS

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# PICT: A low-cost, modular, open-source camera trap system to study plant–insect interactions

**Vincent Droissart**[1,2,3] | **Laura Azandi**[2,3] | **Eric Rostand Onguene**[4,5] | **Marie Savignac**[1,3] | **Thomas B. Smith**[6] | **Vincent Deblauwe**[2,4,6]

[1]AMAP Lab, Université Montpellier, IRD, CNRS, INRAE, CIRAD, Montpellier, France; [2]Herbarium et Bibliothèque de Botanique Africaine, Université Libre de Bruxelles, Brussels, Belgium; [3]Plant Systematics and Ecology Laboratory, Higher Teachers' Training College, University of Yaoundé I, Yaoundé, Cameroon; [4]International Institute of Tropical Agriculture, Yaoundé, Cameroon; [5]National Forestry School Mbalmayo, Mbalmayo, Cameroon and [6]Center for Tropical Research, Institute of the Environment and Sustainability, University of California, Los Angeles, CA, USA

**Correspondence**
Vincent Deblauwe
Email: v.deblauwe@cgiar.org

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## Abstract

1. Commercial camera traps (CTs) commonly used in wildlife studies have several technical limitations that restrict their scope of application. They are not easily customizable, unit prices sharply increase with image quality and importantly, they are not designed to record the activity of ectotherms such as insects. Those developed for the study of plant–insect interactions are yet to be widely adopted as they rely on expensive and heavy equipment.
2. We developed PICT (plant–insect interactions camera trap), an inexpensive (<100 USD) do-it-yourself CT system based on a Raspberry Pi Zero computer designed to continuously film animal activity. The system is particularly well suited for the study of pollination, insect behaviour and predator–prey interactions. The focus distance can be manually adjusted to under 5 cm. In low light conditions, a near-infrared light automatically illuminates the subject. Frame rate, resolution and video compression levels can be set by the user. The system can be remotely controlled using either a smartphone, tablet or laptop via the onboard Wi-Fi. PICT can record up to 72-hr day and night videos at >720p resolution with a 110-Wh power bank (30,000 mAh). Its ultra-portable (<1 kg) waterproof design and modular architecture is practical in diverse field settings. We provide an illustrated technical guide detailing the steps involved in building and operating a PICT and for video post-processing.
3. We successfully field-tested PICT in a Central African rainforest in two contrasting research settings: an insect pollinator survey in the canopy of the African ebony *Diospyros crassiflora* and the observation of rare pollination events of an epiphytic orchid *Cyrtorchis letouzeyi*.
4. PICT overcomes many of the limitations commonly associated with CT systems designed to monitor ectotherms. Increased portability and image quality at lower costs

Vincent Droissart and Vincent Deblauwe contributed equally.

allow for large-scale deployment and the acquisition of novel insights into the reproductive biology of plants and their interactions with difficult to observe animals.

**KEYWORDS**
behavioural ecology, digital video recording, DIY camera trap, e-ecology, low-cost technology, plant–insect interaction, pollination biology, Raspberry Pi

## 1 | INTRODUCTION

Interactions between plants, their pollinators and herbivores have been key in the evolution of flowering plants (Barrett, 2013; Kergoat et al., 2017; Moreau et al., 2006; Schoen et al., 2019). Despite tremendous progress in the fields of pollination biology, quantitative genetics, comparative biology, phylogenetics and genomics, the paucity of empirical data from natural history studies limits progress in understanding pollinator-driven evolution (van der Niet, 2021).

Conventional studies of plant–insect interactions typically involve the collection of data using direct (e.g. Suetsugu, 2019; Tang et al., 2020; Varma & Sinu, 2019) or indirect observations (e.g. Boyer et al., 2020; Johnson et al., 2011). However, because observations are time-intensive, limited by environmental conditions and logistics, they are not conducted over large spatiotemporal scales and often underestimate the importance of furtive organisms compared to larger or slower ones (Micheneau et al., 2006). Furthermore, the presence of a human observer and the need to illuminate the study organism at night may influence its behaviour (Opp & Prokopy, 1986).

Camera trap (CT) technology can greatly advance the study of plant–insect interactions by providing a convenient replacement to classic human observations. This technique have gained popularity because it allows for non-intrusive observations at large spatiotemporal scales and constant sampling effort (Rovero & Zimmermann, 2016; Wearn & Glover-Kapfer, 2019). Recently, camera trapping of insects has become an active field of research and development but important technical limitations still persist (Pegoraro et al., 2020; Preti et al., 2021). First, although it has been reported that the passive thermal infrared motion sensor of commercial CT systems can be activated by large flying insects (Houlihan et al., 2019; Johnson & Raguso, 2016), most ectotherms, such as reptiles, amphibians and invertebrates, do not trigger motion sensors (Hobbs & Brehme, 2017). Moreover, the initial trigger delay has been deemed excessive in many cases, especially in hot environments (Glover-Kapfer et al., 2019; Meek & Pittet, 2012). To circumvent these problems, researchers have developed CT systems relying on active motion detection based on pattern recognition or changes in the successive frames captured by a camera (Barlow & O'Neill, 2020). This technique has proven to be efficient for obtaining data on insect visit frequency, visit duration and for modelling insect activity (Barlow et al., 2017; Steen, 2017). However, applying an on-the-fly motion detection algorithm to filter the video stream during recording increases power consumption and does not allow one to estimate the rate at which motion events fail to be detected. Second, camera characteristics of commercial CT systems often limit the number of taxa that can be accurately identified, especially when taxonomically relevant traits are subtle. Image resolution can often be modulated in the camera settings, but shutter speed decreases as resolution increases, hence decreasing the sharpness of moving animals. Image quality is ultimately limited by the quality of the sensor and the lens, neither of which are interchangeable in most cases (Meek & Pittet, 2012; Rovero et al., 2013). Most CTs use wide-angle fixed-focus lens that are set so that the depth of field ranges from infinity down to a few metres. As a result, these models are not suited for macro-photography. Finally, the cost of CT units is often the limiting factor in terms of the number of sensors that can be deployed simultaneously, and therefore, the statistical power of the analysis. Currently, a mid-range CT costs 200—500 USD (Rovero et al., 2013; Wearn & Glover-Kapfer, 2017). The unit price of motion-triggered CT systems designed for insect monitoring range from 400 EUR (Pegoraro et al., 2020) to several thousands of euros (Danaher et al., 2020; Houlihan et al., 2019).

Here, we propose a new system, called plant–insect interactions camera trap (PICT), that overcomes the above shortcomings. We report results from the deployment of this system under two conditions where manual observation is impossible: (a) in places where an observer cannot remain for long periods of time (pollinator visitation in the canopy of the African ebony tree) and (b) when the time scale involved is too large (low visitation rates of pollinators of an African epiphytic orchid).

PICT contrasts with other solutions by its increased portability, reduced cost and low energy use hardware that does not require heavy and bulky lead batteries to operate. Low-energy consumption is mainly achieved by separating the recording and analysis steps. By providing enough memory to the camera and using an efficient H264 compression algorithm, we can record high definition videos continuously in the field and use a computer to search for the frames of interest later in the lab.

## 2 | DESIGN AND ASSEMBLY

PICT consists of four main components, a single-board computer, a micro SD card, a camera and a USB power bank battery (Figure 1). A practical guide with detailed instructions for constructing PICT as well as the control programs and codes are available online as Supporting Information (Droissart et al., 2021).

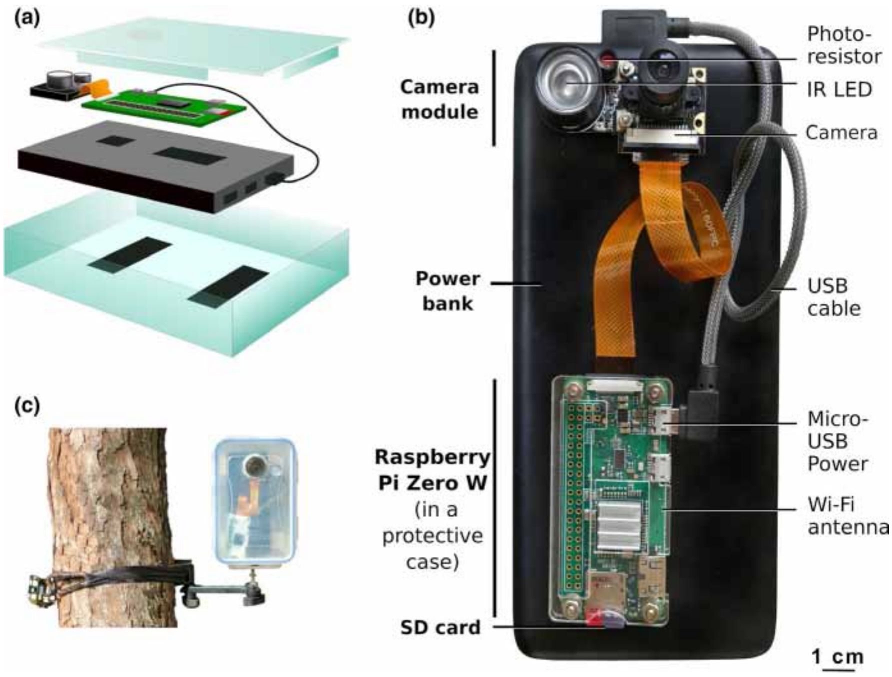


**FIGURE 1** Overview of PICT. (a) Exploded schematic view of PICT with, from top to bottom, lid, Raspberry Pi computer and camera, power bank, food container with epoxy-glued Velcro® strips as black rectangles; (b) Electronic components; (c) PICT mounted on a tree

**TABLE 1** Components used to build the proposed PICT hardware, approximate cost and manufacturer details. Cost ranges represent prices obtained from different online sellers

| Component | Cost (USD) | Model or specification | Manufacturer |
|---|---|---|---|
| Camera body | | | |
| Raspberry Pi | 15–20 | Zero W | Raspberry Pi Foundation |
| Protective case with heatsink | 3–5 | Any | Any |
| Raspberry pi camera with embedded IR-cut and cable | 20–23 | Any | Any |
| Waterproof case | 5–10 | 33.81-oz airtight rectangular | Lock & lock |
| Camera Protective Lens | 2–4 | Any | Any |
| VELCRO strips | 5–10 | Any | Any |
| Epoxy adhesives | 1–2 | Rapid | Araldite |
| Mount with ¼ in screw | 13–20 | Any | Any |
| **Total cost** | **64–94** | | |
| Accessories | | | |
| Power bank with 5V, 2A output | 20–30 | >10,000 mAh | Any |
| 64 GB Micro SD card + SD adapter | 10–15 | SanDiskUltra SDXC class 10 | SanDisk, Milpitas, CA, USA |
| Camera tree mount or tripod with ¼ in screw | 15–30 | Arm with T-Handle; E-Aim Ratchet Strap | Slate River |
| **Total cost** | **45–75** | | |

To protect the components from natural elements, PICT is sealed in a food storage case of about 1 L in volume. Each component inside the case is fixed in place by adhesive Velcro® strips. A mount with a standard ¼ in screw is glued onto the case to allow PICT to be fixed to a standard camera mount. At the time of writing, the full cost of building one operational unit is less than 170 USD. The components needed for a PICT with functionality comparable to a retail CT, that is, without a mount, battery or memory card, would cost less than 100 USD (Table 1).

The camera is operated through the picamera Python package (https://picamera.readthedocs.io/) installed on a Raspberry Pi Zero, which is a credit card-sized, low-cost, high-performance single-board computer. All the Raspberry Pi models with an integrated Wi-Fi controller can provide the functionality required, but we recommend the use of model 'Zero W' for its relatively lower power consumption, price and smaller size. A micro SD card serves as the hard drive on which the operating system, programs and data are stored. It is powered through a 5V mini-USB port that can be supplied by a standard lithium-ion power bank (Figure 1).

We used the 5-megapixel Raspberry Pi Camera Module v1 (OmniVision © OV5647 sensor), based on a 2,592 × 1,944 photosites, ¼ in format sensor. It comes in customized versions with (a) an embedded 3.3V power output that can be connected to a near-infrared LED without need for soldering, (b) a 3.6-mm lens with a diagonal field of view of 75 degrees and adjustable focus distance, (c) no embedded infrared filter, improving lens speed and allowing illumination of the night scene with IR light. To illuminate the scene, we used one 850-nm infrared LED equipped with an onboard photoresistor to decrease light intensity with increasing ambient light. An onboard resistor can be tuned to control the photoresistor ambient light threshold toggling the infrared LED. Near-infrared light is preferred because it is invisible to animals thereby not influencing behaviour. Insects' photoreceptors have a large spectral sensitivity range, but the maximal observed peak absorption wavelength is 630 nm (Briscoe & Chittka, 2001). Positive phototaxis of insects to larger wavelengths has been observed but intensity decreases with increasing wavelength (van Grunsven et al., 2014; Wakakuwa et al., 2014), and is relatively small at 850 nm, as shown for a Coleoptera (Meyer, 1976) and a Hemiptera (Matsumoto et al., 2014).

The image resolution of PICT can be freely determined by the user. Because of the lens characteristics of Raspberry Pi Camera Module v1, the smallest resolvable point is larger than the actual pixel size on the sensor (1.4 × 1.4 μm). For this reason, we recommend setting the resolution to 1,296 by 972 pixels where a 2 × 2 binning is applied by the camera to downsample the image. This camera output resolution has the added benefit of doubling sensitivity and improving the signal to noise ratio. At this resolution, the camera can capture up to 42 frames per seconds (FPS) and up to 90 FPS at 640 by 480 pixels (Barnes, 2020).

## 3 | POWER CONSUMPTION AND DATA STORAGE

Low power consumption is essential to avoid the need for heavy or bulky batteries and to provide autonomous operation times that exceed the duration of the targeted phenomenon (the duration of anthesis for instance). To reduce the power drawn by the PICT by about 0.13W, we deactivated the components that are not needed for our application: the HDMI port, Bluetooth and activity LEDs.

We used an electronic multimeter (RuiDeng UM25C) to measure the power drawn by a PICT under various operating conditions. The observed power load of each of the components and for different camera settings is given in Table 2. We found that both frame rate and resolution settings have a substantial effect on power use (Table 2; Figure S1). We used a resolution of 1,296 by 972 pixels and

**TABLE 2** Power consumption of PICT during typical use desegregated by components and camera settings. Observations were made on a Raspberry Pi Zero W running on Raspberry Pi OS Lite and set-up according to this study recommendations: Camera and IR LED plugged in; HDMI port, Bluetooth and activity LEDs deactivated. When recording, the camera was facing a dark non-moving background. Infrared LED load was observed in plain dark condition. The power drawn on bootup is not accounted here. FPS, frames per second

| Component | Resolution | FPS | Power use (W) |
|---|---|---|---|
| Pi Zero W | | | 0.32 |
| Wi-Fi | | | 0.02 |
| Infrared LED | | | 1.13 |
| Camera | 1,296 × 972 | 10 | 0.37 |
| | | 15 | 0.42 |
| | | 24 | 0.54 |
| | | 42 | 0.81 |
| | 640 × 480 | 10 | 0.30 |
| | | 15 | 0.36 |
| | | 24 | 0.41 |
| | | 42 | 0.58 |
| | | 90 | 0.64 |
| RPi Cam[a] | 1,296 × 972 | 15 | 1.65 |
| MotionEye[a] | 1,296 × 972 | 15 | 1.33 |

[a]Total power drawn by the RPi Cam Web Interface and MotionEyeOS performing motion detection with LED switched off.

15 frames per second (FPS) to achieve the lowest possible power consumption and storage needs while not affecting the ability to identify insects. With these settings and with Wi-Fi switched off at night, the PICT will draw only 0.76 and 1.87 W, respectively, during the day and at night. This theoretically permits continuous filming for over 72 hr with a 30,000-mAh (111 Wh) power bank, as was confirmed during field deployment. With these settings, PICT would be able to run for almost 9 days if recordings are performed during the day only and the IRD LED is not connected (Figure S1).

We advocate the application of motion detection algorithms as a post-processing stage rather than in situ because the processing of the video stream to filter out still sequences is computationally expensive. The additional power drawn will directly depend on the algorithm complexity. As a comparison, an extra 0.89 and 0.57 W are needed by the motion detection algorithms implemented in RPi Cam Web Interface (https://github.com/silvanmelchior/RPi_Cam_Web_Interface) and MotionEyeOS (https://github.com/ccrisan/motioneye) respectively (Table 2) which would increase power draw over 24 hr (with 12 hr of daylight) by *c*. 67% and 43% respectively.

Once the operating system is installed on a 64 GB micro SD card, 57 GB will remain free for data. The videos are saved on the micro SD card as MP4 files encoded in H.264 compression standard. A video recording of 1 hour at default compression, and above settings in outdoor conditions would take up around 700 MB. Therefore, storage space is not a limiting factor, as the battery would run out before the storage media get saturated. Furthermore, we noticed no compression artefact when reducing file size by a factor of 2 using a higher compression level, thus allowing for further increase in storage efficiency if needed.

## 4 | VIDEO ANALYSIS

Processing of videos or pictures is time- and computer power-intensive. The choice of post-processing the data, rather than in situ motion detection, allows for decreasing power consumption and processor temperature and for fine-tuning the motion detection threshold of the algorithms based on the rate of omission. Motion detection techniques applied as a post-process to filter video recordings have been proven effective in detecting pollinator activity (Azarcoya-Cabiedes et al., 2014; Weinstein, 2015). In our study, motion detection post-processing was found useful in the case of rare and brief visits but not when visits are frequent. Two post-processing algorithms are presented in the practical guide available as Supporting Information (pp. 36–39).

## 5 | FIELD TESTING

### 5.1 | Deployment and data processing

To assess the performance of PICT in the field, we studied two plant species with contrasting habits, pollination ecologies and floral characteristics: the African Ebony tree *Diospyros crassiflora* Hiern and the epiphytic orchid *Cyrtorchis letouzeyi* Szlach. & Olszewski.

*Diospyros crassiflora* is a commercially valuable ebony tree native to the rainforests of Central Africa that can reach 25 m in height. Until this study, the identity of its pollinators was unknown (Deblauwe, 2021). Staminate and carpellate flowers are found on different plants, a character known as dioecy. We considered as potential pollinators all insects that entirely enter the narrow opening (*c*. 5 mm wide) of the fused petals of the corolla. PICTs were placed at dusk in the canopy of two *D. crassiflora* trees (4–10 m above the ground), in front of a single flower estimated to reach anthesis the following night, from 6 to 14 April 2018 in Mbalmayo arboretum, Cameroon. In total, four flowers were observed. Time of arrival and departure and identity of insects visiting the flowers were observed based on video analysis. Every time an insect entered a flower entirely, from head to abdomen, was considered as a single independent visit.

*Cyrtorchis letouzeyi*, a sub-endemic orchid primarily found in Cameroon, is remarkable for its ivory white flowers with a nectar spur measuring up to 10 cm in length. The flowers emit a strong lilac/jasmine scent at night. This epiphytic species is easily observed growing at a height of 1–3 m on shrubs bordering the grasslands on inselbergs of the Dja Faunal Reserve (East Cameroon). Pollination syndromes suggest that this species could be visited by long-tongued hawkmoths (Cribb, 1989), but this had not yet been confirmed by field observations. PICTs were placed in front of six flowering individuals bearing at least two inflorescences and 10 flowers each, during two consecutive flowering periods in 2018 (24 June to 15 July) and 2019 (24 June to 14 July). Batteries and micro SD cards of each PICT were replaced every 48 hr.

To detect motion in the videos of the orchid flowers during post-processing, we used our own MATLAB © routine. The same motion sequences were detected by the open-source cross-platform command-line tool DVR-Scan (https://dvr-scan.readthedocs.io). Because of the high insect visitation frequency, automatic detection was not necessary to remove still sequences from videos of the African ebony flowers. Videos were analysed manually by watching the full sequences at 8× speed using VLC media player open-source software.

### 5.2 | Results

We recorded a total of 76.3 hr of African ebony flowers at anthesis stage. The only occasion that a non-insect was seen interacting with the flowers was of a flying squirrel (*Anomalurus* sp.) predating a flower before anthesis (Video S1). Flowers were fully open around midnight and dropped about 20 hr later, just after dusk. In total, the antheses of five flowers were recorded (four staminates and one carpellate) and 394 independent visits were observed in the videos. We identified five taxa in three families (two orders) of insect visiting the flowers: *Thrinchostoma* sp. (Halictidae), *Ceratina* sp., *Plebeina hildebrandti* Friese, *Meliponula (Meliplebeia) nebulata* Smith (Apidae) and one Sphingidae. Up to 141 independent visits per flower were observed and were concentrated during the daytime. The nocturnal *Thrinchostoma* spp. bees were relatively rarely observed, but being the first to enter the flowers, they are potentially an important pollinator species (Figure 2). One of the visitors, *Apis mellifera* Linnaeus

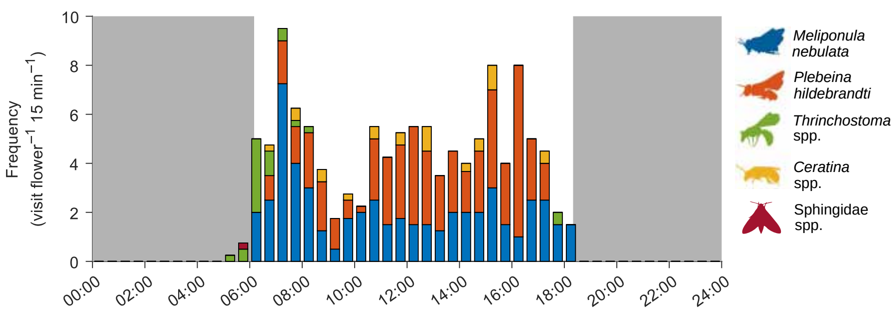


**FIGURE 2** Effect of time of day on African ebony *Diospyros crassiflora* flowers visitation rates. Every taxon observed entering the flowers or sucking nectar at least one time is represented. Grey shadings indicate night-time

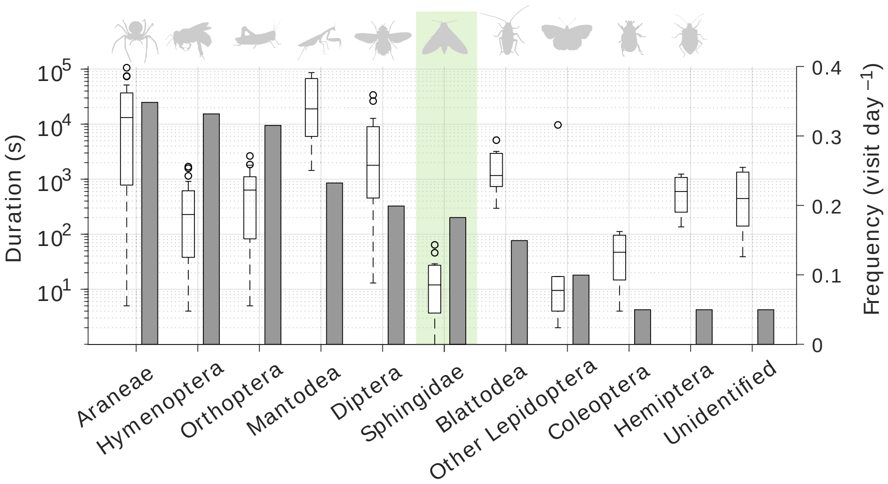


**FIGURE 3** Duration (boxplots) and frequency (bars) of visits of different orders of insects on the African epiphytic orchid *Cyrtorchis letouzeyi*. Pollination events are shown in green

was only observed twice, each time on a different flower. The opening of the corolla is too small for it to enter the flower (Video S1) and the species is therefore not represented in Figure 2.

A total of 1,447 hr of *Cyrtorchis letouzeyi* flowers were monitored by PICT during two field campaigns in 2018 and 2019. Post-processing to detect sequences with motion resulted in 66 hr of summary video files. Only 121 of the 166 registered insects were in contact with the flower. Flowers were visited by taxa from ten taxonomic Orders of insects (Figure 3). The pollinators of *C. letouzeyi*, the Sphingidae *Xanthopan morganii* Walker and *Coelonia fulvinotata* Butler were observed only 13 times on video. Pollen transfers and resulting fecundation were confirmed by video showing the attachment of *C. letouzeyi* pollinaria on the probosces of the visiting hawkmoth (see example in Video S2) and by daily, manual observations of flowers and the development of fruits. The mean visit duration of confirmed pollinators was 19.6 s (±20.7 s, *SE*). The rate of pollinarium removal was 25.3% (84/332 flowers) and that of fruit set was 6.3% (21/332 flowers) for the entire population (31 individuals) over the 2-year survey.

## 6 | DISCUSSION

Our results demonstrate that PICT resolves many of the limitations commonly associated with both CTs designed to monitor ectotherms and conventional CT systems (Meek & Pittet, 2012; Rovero et al., 2013): (a) Low powered CT system. PICT power draw is about 32 Wh per day (with 12 hr of daylight) when recording video with recommended settings, which allows for up to 72 hr of continuous video recording with a 30,000-mAh power bank. (b) Customizable video acquisition setting and high image quality. Most CTs use proprietary technologies, preventing users from modifying specific options for image or video acquisition. At a resolution of 1,296 by 972 pixels, PICT provided a clear, sharp image which allowed identifying pollinators down to the genus or species level (Video S1–S3). (c) Modular architecture. Interchangeable sensor and lens, as well as adjustable focus lenses permit the observation of organisms of all sizes. Lenses with a wide range of focal lengths are available, from fisheye to telephoto lenses. To the best of our knowledge, there is currently no commercial CT able to film insects smaller than about 5 cm. (d) Portability. PICT components weigh around 250 g. The battery weighs 450–690 g, respectively, for the 22,000 and 30,000 mAh model we tested. The total weight is substantially less than similar CT systems recently proposed in the literature (e.g. Clayborn & Clayborn, 2019; Houlihan et al., 2019; Nazir et al., 2017; Steen, 2017). (e) Remote control. The control, live view and data transfer through Wi-Fi with a smartphone, a tablet or a laptop facilitate camera placement and monitoring in places that are difficult to access. (f) Low-cost components. The unit price is less than USD 100 (Table 1) and a suite of free software can be used to operate PICT and analyse the data.

We designed PICT so as to maximize power efficiency and portability and to minimize cost. The main limitations of PICT are a consequence of these choices. First, the autonomy is limited to 3 days when recording outdoor videos continuously. PICT autonomy depends only on power bank capacity. Data storage of PICT is not a limiting factor because the widely available and inexpensive 64 GB micro SD card is sufficient to store more than 3 days of film at default compression level and recommended settings (resolution of 1,296 by 972, 15 FPS). The autonomy of PICT can easily be improved by providing extra power to the power bank using a USB solar panel (a process known as pass-through charging technology). When an external power source is available to film for longer periods of time, then the storage capacity might become limiting. In that case, the extra power from the external source might allow active in situ motion detection to save space on the storage media. This could be implemented using open-source libraries available for Raspberry Pi (e.g. https://github.com/Motion-Project/motion and https://opencv.org/). This technique is relevant when post-processing time or data storage space needs to be reduced. However, in the absence of external power source, either autonomy or portability would be sacrificed to power the motion detection algorithm.

Second, the durability of the Raspberry Pi in harsh environments can be affected by electrostatic damage, flaws in the sealing or mishandling of the plastic container. Occasional malfunction of electronic components has not however posed a substantial challenge in our experiments due to the ease and low-cost of acquiring spare parts to repair possible damages.

Finally, PICT is designed to be controlled remotely via Wi-Fi. In open area, we were able to smoothly control PICT from over 100 m away with a smartphone emitting its own Wi-Fi network. We expect this distance to decrease substantially in obstructed environments, and the operator would probably require the use of Wi-Fi repeaters if longer distance wireless supervision is required.

A wide range of environmental sensors are available for Raspberry Pi computers. The computational power, versatility and connectivity of the computer allow more complex tasks to be performed. If the need arises, PICT can interact through wireless technology embedded in the Raspberry Pi computer (Bluetooth or Wi-Fi) with any nearby devices, including other PICTs, or a remote machine through the Internet. With minor modifications made to the system we present here, we believe that PICT could be used in a wide range of both in situ and ex situ experiments, for instance to document insects' social and predator–prey interactions, the effect of (micro) climate change on their activity or herbivory and plant phenology.

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## AUTHORS' CONTRIBUTIONS

V.Dr. and V.De. conceived the idea; V.Dr., V.De., L.A., M.S. and E.R.O. deployed PICT in the field and collected the data; V.De., L.A. and M.S. analysed the data; V.Dr. and V.De. wrote the manuscript with input from L.A., M.S., T.B.S. and E.R.O.; All authors contributed to improve the first draft of the practical guide written by M.S.; V.De., V.Dr. and M.S. designed the figures; V.Dr. assembled and edited the video clips provided as Supporting Information. All authors gave approval for publication.

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## PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/2041-210X.13618.

## DATA AVAILABILITY STATEMENT

A practical guide with computer code and step by step instructions for building PICT, using in the field and post-processing movies is archived at https://doi.org/10.5281/zenodo.4139839 (Droissart et al., 2021).

## ORCID

*Vincent Droissart* https://orcid.org/0000-0001-9798-5616
*Laura Azandi* https://orcid.org/0000-0002-8709-4606
*Eric Rostand Onguene* https://orcid.org/0000-0003-0886-0833
*Marie Savignac* https://orcid.org/0000-0001-9366-6861
*Thomas B. Smith* https://orcid.org/0000-0002-5978-6912
*Vincent Deblauwe* https://orcid.org/0000-0001-9881-1052

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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