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SHORT COMMUNICATION

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Refuge by day, forage by night: Diel activity of vine weevil as characterised by smart monitoring

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Abstract

1. Vine weevil (*Otiorhynchus sulcatus*) is a major pest of soft fruit and ornamental crops whose nocturnal habits make monitoring challenging and understanding their diel activity is critical for improving detection and informing the timing of control measures.
2. A smart monitoring tool equipped with imaging and environmental sensors was used to monitor adult vine weevil behaviour under semi-field conditions, capturing 794 detections across 720 ten-min intervals over 5 monitoring days.
3. Weevil detections were higher during photophase than scotophase (mean ± SE: 9.48 ± 0.76 vs. 1.10 ± 0.50 weevils h^{-1}), indicating refuge-seeking behaviour in response to increasing light intensity.
4. Generalised linear mixed models identified a strong effect of light condition on weevil activity, with detections 9.5 times more likely during daylight (rate ratio = 9.47, 95% confidence interval [CI]: 4.84–18.52) and presence odds 81 times greater (odds ratio = 81.0, CI: 10.2–645.2; $p < 0.001$)
5. These results provide direct behavioural evidence of diel activity rhythms in vine weevil, supporting its classification as a nocturnal forager that aggregates in refuges during the day.
6. Smart monitoring systems offer a scalable method for characterising pest behaviour in horticultural environments and can support more effective, behaviourally informed integrated pest management interventions.

KEYWORDS
diel activity, integrated pest management, light intensity, nocturnal behaviour, *Otiorhynchus sulcatus*, refuge-seeking, smart monitoring, vine weevil

INTRODUCTION

Vine weevil, *Otiorhynchus sulcatus* (Fabricius, 1775; Coleoptera: Curculionidae), is one of the most economically important pest species in global soft fruit and ornamental crops (Pope & Roberts, 2022). Adult feeding typically occurs at night and results in characteristic notching along leaf margins (Moorhouse et al., 1992). Such above-ground damage is considered unacceptable under ornamental plant quality standards and severe infestations can markedly reduce the market value of affected plants (Pope & Roberts, 2022). Larvae feed on roots and crowns, reducing plant vigour and causing mortality in severe cases (Moorhouse et al., 1992). The combination of nocturnal feeding by

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adults and the largely subterranean lifestyle of larvae presents substantial challenges for detection, monitoring and timely implementation of control measures (Pope & Roberts, 2022). Effective integrated management therefore requires a detailed understanding of vine weevil ecology and behaviour. Previous work has examined the olfactory and visual preferences of adults to develop attractants and improve monitoring tools (Fezza et al., 2023; Roberts et al., 2019), but comparatively little attention has been given to their diel activity under realistic production conditions. Yet, information on when adults are most active is critical for optimising the timing of crop inspections, deployment of monitoring devices and application of biological or chemical control agents, thereby improving detection accuracy and overall control efficiency.

Studies on other weevil species indicate that adult behaviour and movement can be strongly influenced by light. In alfalfa weevil (*Hypera postica* Gyllenhal; Coleoptera: Curculionidae), adults remain within ground debris or on the underside of lower, dried leaves of alfalfa (Fabales: Fabaceae) plants during daylight, but after sunset become active, moving away from the plant base, crawling upwards to feed and remaining on the foliage throughout the night (Poinar Jr & Gyrisco, 1964). Similarly, Aldryhim and Ayedh (2015) described diel activity patterns of red palm weevil (*Rhynchophorus ferrugineus* Olivier; Coleoptera: Curculionidae) in the field using a smart trap, generating information that helped to optimise the timing of pesticide applications and other interventions. Vine weevil adults are believed to be most active and to feed primarily between dusk and midnight (Smith, 1932), and as dawn approaches, they move to refuges where they aggregate (Fezza et al., 2023; van Tol et al., 2012). Although environmental factors such as light, temperature and humidity are likely to play a key role in regulating this behaviour, their influence on vine weevil diel activity has not been quantified under field or semi-field conditions. Improved understanding of activity patterns in the natural or production environment would help to refine their management within integrated pest management (IPM) programmes.

The present study was designed to quantify the diel activity of adult vine weevil under semi-field polytunnel conditions using a smart monitoring trap capable of continuously recording insect activity over successive 24-h cycles. This approach provides new information on the temporal dynamics of adult activity under realistic environmental conditions and supports the development of behaviourally informed monitoring strategies for sustainable horticultural production.

MATERIALS AND METHODS

Insects

Adult vine weevils were collected by hand from an organic strawberry farm in Staffordshire, United Kingdom (52.97595° N, 2.38774° W) during summer 2025. These individuals were maintained in plastic terraria (Exo Terra, Castleford, UK; 30 × 19.3 × 20.6 cm) and supplied with Fortune's spindle, *Euonymus fortunei* (Turcz. Hand.-Maz.; Celastrales: Celastraceae), as a food source. A piece of moist tissue paper was provided for hydration and a cotton wool ball was supplied as an oviposition substrate. Food, hydration and oviposition substrates were replaced weekly. Terraria were held in controlled-environment chambers (Fitotron, Weiss Technik, Loughborough, UK) at 20°C, 60% relative humidity (RH) and a 16 : 8 light : dark photoperiod. Adults used in experiments originated from the field-collected generation and of unknown exact age, as is typical for field-caught vine weevil populations, but maintained under laboratory conditions for a minimum of 4 weeks to ensure acclimatisation.

Smart monitoring tool design

The smart monitoring tool used in this study was previously described in Zhao et al. (2025) and had three primary components. First, the electronics module housed a Raspberry Pi Zero 2 W (Raspberry Pi Foundation, Cambridge, UK) connected to a Raspberry Pi Camera Module 2 (V2.1; PiHut, Haverhill, Suffolk, UK), an external USB flash drive (SanDisk Ultra Flair USB 3.0, SanDisk, California, USA) for image storage and sensors to measure environmental conditions such as light intensity (BH1750FVI lux sensor) and temperature/humidity (BME280). Second, a black cone constructed from polyethylene served as a visual attractant for vine weevils (Fezza et al., 2023). Third, an imaging platform positioned at the base of the cone provided the surface on which adults were recorded and which also functioned as a refuge used by adults during the day. The system was powered via a 12 V battery and controlled using a custom script to trigger image capture at fixed 10-min intervals.

Experimental setup

Experiments were carried out in a commercial style polytunnel near Newport, Shropshire, UK (52.776098° N, 2.428374° W) between July and September 2025. During this period, temperature averaged 23.8 ± 8.7°C (photophase: 27.9 ± 8.0°C; scotophase: 15.9 ± 2.4°C) and RH averaged 57.9 ± 20.5% (photophase: 47.9 ± 18.0%; scotophase: 77.2 ± 6.4%). Two mesh tent cages (145 × 145 × 152 cm; Insectopia, Austrey, UK) containing four potted strawberry plants, *Fragaria* × *ananassa* Duch. cv. Elsanta, grown in 13 cm diameter pots (Teku VCH13, Pöppelmann, Lohne, Germany) with a coir-based substrate (Cocogreen Berryfusion O2 Coir, Manchester, UK) were used as experimental arenas. Two cages were setup to facilitate arena alternation between days. Pots were arranged in a square, 55 cm apart, with the smart monitoring tool positioned centrally between the four plants. These plants were provided to act as both a food source and shelter. Although the smart monitoring tool recorded light intensity via the integrated BH1750FVI sensor, an independent HT.w Sensor (SensorPush, New York, USA) was deployed at canopy height (i.e., 10 cm above substrate surface) within the tent cage to provide validated temperature and humidity measurements at canopy height, independent of the monitoring device microclimate. Environmental measurements were logged throughout the monitoring periods to provide contextual data for interpretation of activity patterns.

Forty adult vine weevils were released into the tent cage at 4:00 PM by placing them at the base of the central area between the strawberry plants. The smart trap was programmed to capture images every 10 min continuously for 24 h (4:00 PM to 4:00 PM). At the end of each 24-h period, adults were removed, plants were checked and, where necessary, replaced to maintain comparable canopy structure, and the system was reset. The 24-h monitoring run was repeated five times on different days, using fresh adults for each tent cage replicate ($n = 5$), yielding a total of 720 10-min intervals for analysis. For each image, the number of adult vine weevils visible on the imaging platform was counted manually and recorded as the number of weevils detected at 10-min intervals. These count data were matched to time-stamped light, temperature and humidity measurements to create a continuous time series of adult activity and environmental conditions.

Statistical analysis

Weevil activity was recorded as the number of individuals detected within the monitoring devices at 10-minute intervals across five 24-h monitoring periods. To reduce temporal autocorrelation, data were aggregated to hourly totals prior to analysis. Each monitoring period ran from 4:00 PM to 4:00 PM, spanning two calendar dates; observations were therefore grouped by trial day (1–5) rather than calendar date, yielding 120 hourly observations (5 trials × 24 h). Observations were classified into photophase (light intensity >0 lux; $n = 79$) and scotophase (light intensity = 0 lux; $n = 41$) periods based on real-time measurements from the integrated light sensor. The effect of light condition on hourly weevil counts was analysed using generalised linear mixed models (GLMMs) with a log-link function. Trial day and hour of day were included as random intercepts to account for day-to-day variation in baseline activity and temporal pseudoreplication arising from individual weevils potentially remaining in the refuge across consecutive hours, respectively. Temperature and RH were examined as fixed covariates; both were strongly correlated with light intensity (temperature–LUX: $r = 0.93$; RH–LUX: $r = -0.83$), and RH was retained as a covariate where it improved model fit. Three candidate error distributions were compared: Poisson, Poisson with an observation-level random effect to account for overdispersion, and negative binomial. Model selection was based on Akaike Information Criterion (AIC); the negative binomial model provided the best fit and was retained for inference (Table S1). A complementary presence/absence analysis was carried out using a binomial GLMM with a logit-link function, applying the same random effect's structure. The effect of light condition was expressed as the incident rate ratio (RR) for count data and odds ratio (OR) for presence/absence data, with 95% confidence intervals calculated using Wald-type approximations. Model fit was assessed using DHARMa residual diagnostics, including tests for uniformity, dispersion, and zero-inflation. All analyses were carried out using R version 4.4.0 (R Core Team, 2024) using the lme4 (Bates et al., 2014) and DHARMa (Hartig, 2024) R packages. Full model specifications, parameter estimates, and fit statistics are provided in Tables S1–S6.

RESULTS AND DISCUSSION

A total of 794 vine weevil detections were recorded across 720 observation intervals, which were aggregated to 120 hourly observations for analysis. Mean temperature across the monitoring period was 23.8 ± 8.7°C (photophase: 27.9 ± 8.0°C; scotophase: 15.9 ± 2.4°C) and mean RH was 57.9 ± 20.5% (photophase: 47.9 ± 18.0%; scotophase: 77.2 ± 6.4%). Both variables were strongly correlated with light intensity (temperature–LUX: $r = 0.93$; RH–LUX: $r = -0.83$). Vine weevil presence within the monitoring tool showed a pronounced diel pattern strongly associated with photoperiod (Figure 1). During photophase periods ($n = 79$ hourly observations), weevils were detected at a mean (± SE) rate of 9.48 ± 0.76 individuals per hour, with at least one weevil present in 93% of observations. In contrast, during scotophase periods ($n = 41$ hourly observations), the mean detection rate was 1.10 ± 0.50 individuals per hour, with weevils present in only 26% of observations. This difference was highly significant, with weevils 9.5 times more likely to be detected during photophase compared with scotophase (RR = 9.47, 95% CI:4.84–18.52, $z = 6.57$, $p < 0.001$; Tables S2.1 and S2.2). The comparatively low count at 4:00 PM reflects the trial initiation; weevils had been freshly released and had not yet located the monitoring device as a refuge. Including RH as a fixed covariate improved model fit (ΔAIC = 5.0), though light condition remained the primary predictor of weevil counts (RH coefficient = −0.022, $p = 0.008$; Tables S3.1 and S3.2). A complementary presence/absence analysis corroborated this finding, indicating that the odds of detecting at least one weevil were 81 times higher during photophase than scotophase (OR = 81.0, 95% CI: 10.2–645.2, $z = 4.15$, $p < 0.001$; Tables S4.1 and S4.2). Analysis by period provided further resolution of the temporal activity pattern. Predicted hourly counts were lowest during nocturnal hours (10:00 PM to 04:59 AM; 0.19 weevils per hour, 95% CI: 0.08–0.43), increasing substantially during morning (05:00 AM to 11:59 AM; 8.08, 95% CI: 5.47–11.93), afternoon (12:00 PM to 05:59 PM; 10.05, 95% CI: 6.77–14.94) and evening (06:00 PM to 09:59 PM; 7.56, 95% CI: 4.84–11.82) (Tables S5.1–S5.3). All daytime periods differed significantly from night ($p < 0.001$), whereas morning, afternoon, and evening counts did not differ significantly from one another ($p > 0.05$). When light intensity was modelled as a continuous predictor, there was a significant positive relationship with weevil counts (coefficient = 0.287 ± 0.041, $z = 7.06$, $p < 0.001$; Tables S6.1 and S6.2), with each unit increase in log(LUX + 1) associated with a 1.33-fold increase in expected count. The random effects structure captured modest variation attributable to trial day ($\sigma = 0.35$) and hour of day ($\sigma = 0.62$), indicating that while baseline activity varied somewhat between days, the fundamental diel pattern remained consistent throughout the monitoring period.

The findings from this study provide strong evidence that the smart monitoring tool functions as a daytime refuge, effectively exploiting the adult vine weevil's thigmotactic behaviour. Vine weevils

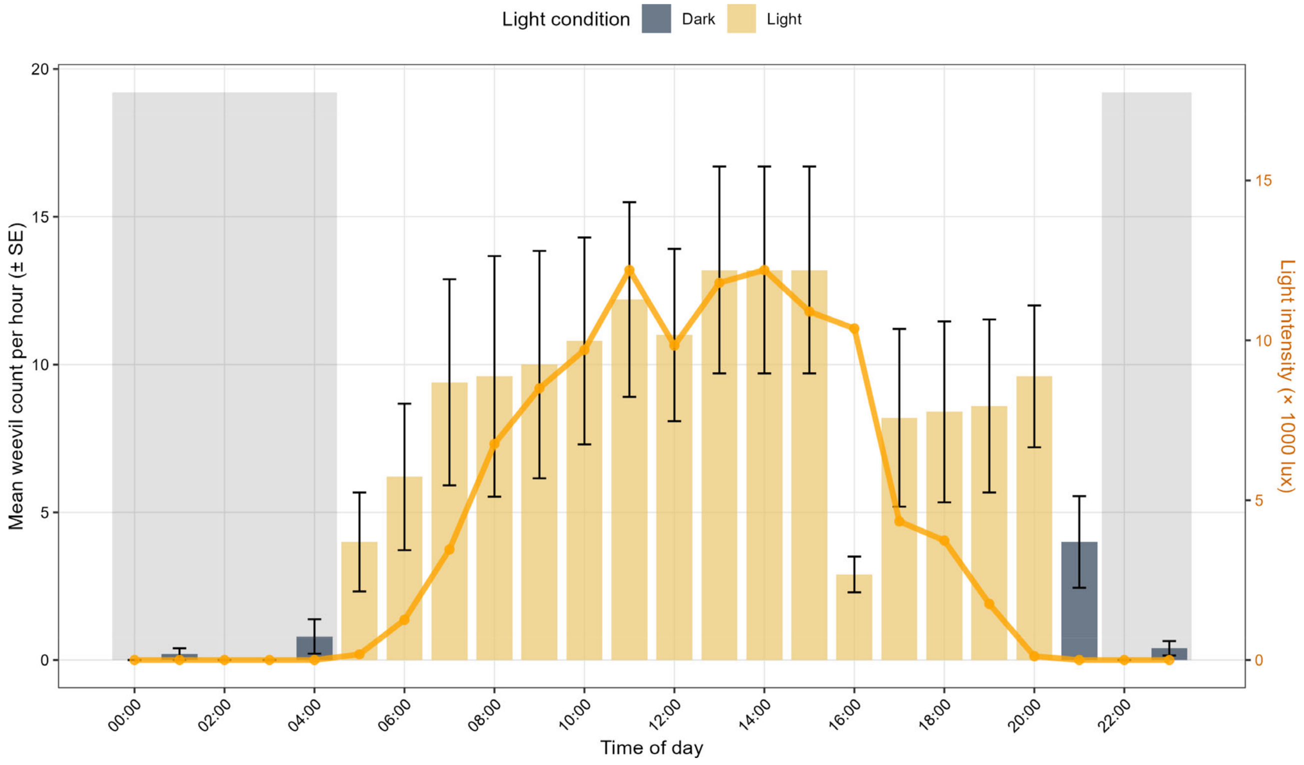

FIGURE 1 Diel activity pattern of adult vine weevil within a smart monitoring device under semi-field conditions. Bars represent mean (± SE) hourly weevil count across five monitoring days. Bar colour indicates photophase (light; yellow) and scotophase (dark; grey) periods based on real-time light intensity measurements. The orange line shows mean light intensity ($\times 10^3$ lux). Grey shading denotes scotophase periods (light intensity $= 0$ lux). Weevil presence in the monitoring device was 9.5 times higher during photophase than scotophase, consistent with daytime refuge-seeking behaviour. The lower count at 4:00 PM reflects the trial start time; weevils had been freshly released and had not yet located and occupied the monitoring device as a refuge.

are well-documented nocturnal feeders that seek concealed harbourage during daylight hours, sheltering beneath debris, within soil crevices, or under plant material to avoid predation and desiccation (Moorhouse et al., 1992; Son & Lewis, 2005a). This refuge-seeking behaviour is common among nocturnal Curculionidae and reflects both predator avoidance and physiological constraints on water balance during warm, bright conditions (Leather et al., 1999). The monitoring tool, with its baseplate, provides an effective artificial refuge that weevils readily occupy during photophase. A 9.5-fold higher detection rate during daylight demonstrates that this behavioural exploitation is highly effective for monitoring purposes. The strong positive relationship between continuous light intensity and vine weevil counts further supports the refuge-seeking interpretation. As ambient light increased, so too did the number of weevils occupying the dark interior of the monitoring device, suggesting active behavioural avoidance of illuminated environments. This photonegative response is consistent with the general biology of many nocturnal Coleoptera (Bell, 1990; Jander, 1963) and has been documented in other economically important weevils, including the boll weevil *Anthonomus grandis* (Greenberg et al., 2006) and the large pine weevil *Hylobius abietis* (Leather et al., 1999). Circadian control of such phototactic responses is well established in insects (Tomioka & Matsumoto, 2010) and the consistency of the diel pattern observed across all monitoring days suggests robust endogenous rhythmicity in vine weevil refuge-seeking behaviour.

The low number of individuals during scotophase (mean 1.10 per hour versus 9.48 during photophase) corresponds with their expected nocturnal foraging activity. Adult vine weevils emerge from refugia after dark to feed on host plant foliage, typically causing the characteristic notching damage to leaf margins that serves as a diagnostic indicator of infestation (Cowles, 2004; Moorhouse et al., 1992). The low but non-zero scotophase counts likely represent individuals that had not yet departed for foraging, were returning from feeding bouts, or exhibited atypical behaviour due to environmental conditions. The crepuscular transition periods showed intermediate detection rates, consistent with the gradual movement of weevils to and from refugia at dawn and dusk, as has been observed in other nocturnal beetles (Lövei & Sunderland, 1996). The consistency of this pattern across all monitoring days, evidenced by the relatively modest random effect variance for date ($\sigma = 0.35$), suggests that the diel rhythm of refuge use is robust and predictable under the environmental conditions experienced during mid-summer. This consistency has important practical implications for the deployment of smart monitoring systems, as it indicates that standardised sampling protocols can be developed with confidence that the fundamental behavioural response will remain stable. The optimal window for assessing weevil presence appears to be during mid-morning to late afternoon (approximately 11:00 AM to 08:00 PM), when detection rates were consistently highest. Conversely, nocturnal sampling would substantially underestimate population abundance, with predicted counts approaching zero between 10:00 PM and 04:00 AM.

This study demonstrates proof-of-concept for smart monitoring of vine weevil populations based on exploitation of their natural refuge-seeking behaviour. Traditional monitoring approaches for this pest have relied on destructive root sampling, visual inspection of plant damage, or the use of refugia traps such as grooved boards and corrugated cardboard that require manual checking at regular intervals (Roberts et al., 2020). These methods are largely ineffective, labour-intensive and provide periodic snapshots of population status. The integration of automated detection within an artificial refuge offers the potential for continuous, real-time population monitoring without the labour requirements of conventional methods, aligning with broader developments in smart agricultural technologies (Cardim Ferreira Lima et al., 2020; Preti et al., 2021). Recent advances in automated pest monitoring have demonstrated the feasibility of camera-equipped traps (Ding & Taylor, 2016; Doitsidis et al., 2017), sensor-based detection systems (Potamitis et al., 2018) and machine learning approaches for pest identification (Li et al., 2021; Zhao et al., 2025). The clear diel signal observed in the present study suggests that detection algorithms for vine weevil could be optimised to focus on photophase periods, potentially reducing data processing requirements while maintaining high sensitivity.

With a maximum mean hourly detection of approximately 9.5 individuals from a known population of 40 (approximately 24%), the smart monitoring device captured a reasonable proportion of the available population during the photophase. This detection rate is consistent with the range of 0.4% to 26.7% reported across six different vine weevil monitoring tool designs under semi-field conditions (Roberts et al., 2020), and sits at the upper end of that range despite operating passively without the addition of semiochemical lures. The addition of kairomone-baited lures, such as (*Z*)-2-pentenol, has been shown to further increase refugia trap catches by over 50% (van Tol et al., 2020), suggesting that detection rates for the smart monitoring device could be improved through integration of chemical attractants. It is important to note that absolute detection rates for refugia-based monitoring of flightless, ground-dwelling Coleoptera are expected to be lower than those achieved by pheromone-baited traps for flying Lepidoptera, because interception depends entirely on the probability that walking individuals encounter the device during their nocturnal foraging activities (Fezza et al., 2022; Pope & Roberts, 2022). However, for IPM decision-making, the capacity of a monitoring tool to reliably detect population presence and track relative changes in abundance over time is arguably more important than the absolute proportion of the population captured at any single time point (Pope & Roberts, 2022). The consistent diel pattern of detection observed in the present study, with predictable peaks during the photophase, reinforces the reliability of the smart monitoring device for generating actionable population data.

The present study was carried out using potted strawberry plants, which present a relatively low, open canopy architecture with minimal structural complexity between the soil surface and the plant foliage. This cropping environment likely facilitated access by adult vine weevils to the ground-level monitoring device, as individuals returning from nocturnal feeding on foliage would encounter few physical barriers during their descent to seek diurnal refugia. In taller or structurally more complex crop canopies, such as containerised rhododendron, *Taxus*, or other hardy ornamental nursery stock, canopy height and density may influence detection rates in several ways. First, the greater vertical distance between the feeding zone in the upper canopy and the soil surface increases the path length that adults must traverse, potentially reducing the proportion of the population that reaches ground-level refuges within a given time period. Mark-recapture studies have demonstrated that adult vine weevil dispersal is limited, with distances of 6.8–31.2 m over 21–57 days respectively (Maier, 1978), and the dense branching structure of shrubby hosts may provide alternative concealed resting sites within the canopy itself, thereby reducing reliance on ground-level refugia (Moorhouse et al., 1992; Pope & Roberts, 2022). Second, in commercial nursery production, containerised stock is frequently grown on raised benches or standing ground, which alters the spatial relationship between plant canopy and soil surface and may necessitate modification of monitoring device placement. Refuge design features such as dark colouration and basal entrance openings, which are preferred by adult vine weevils (Fezza et al., 2022), and the use of flexible refuge materials that can be wrapped around stems or placed within dense ground cover (van Tol et al., 2020), offer potential solutions for adapting monitoring tools to different crop architectures. Validation of the smart monitoring system across contrasting production systems and canopy structures, including both soft fruit and ornamental nursery crops, is therefore warranted to establish the generality of the detection patterns observed here.

Several considerations should inform the further development and deployment of this monitoring approach. First, the present study was conducted under semi-field conditions with a known weevil population and validation under commercial production settings with variable population densities will be essential. Second, the relationship between refuge occupancy and absolute population size requires calibration; while higher detection rates presumably indicate larger populations, the precise quantitative relationship remains to be established through mark-recapture or comparative sampling studies. Third, environmental factors beyond light intensity may influence refuge use under conditions more extreme than those experienced during this study. Although vine weevil activity is known to be temperature-dependent (Son & Lewis, 2005b), it is correlated with photophase periods, and seasonal variation in refuge use patterns warrants investigation. Adult vine weevils exhibited a pronounced diel pattern of refuge use, with detection rates in the smart monitoring device 9.5 times higher during photophase than scotophase. This pattern was consistent across monitoring days and strongly correlated with ambient light intensity, confirming that the device effectively exploits the natural refuge-seeking behaviour of this economically important pest. These findings establish a behavioural foundation for the development of automated monitoring systems targeting vine weevil in soft fruit and ornamental production systems, contributing to the growing toolkit of smart technologies for IPM.

AUTHOR CONTRIBUTIONS

Ronald Manjoro: Data curation; investigation; methodology; writing – original draft; writing – review and editing. **Eugenia Fezza:** Methodology; writing – original draft; writing – review and editing; supervision. **Matt Butler:** Methodology; writing – original draft; writing – review and editing. **Mike Gutteridge:** Methodology; writing – original draft; writing – review and editing. **Tom W. Pope:** conceptualization; methodology; writing – original draft; writing – review and editing; supervision; funding acquisition. **Joe M. Roberts:** Conceptualization; data curation; formal analysis; methodology; visualisation; writing – original draft; writing – review and editing; supervision; funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data from this manuscript are available here: https://doi.org/10.6084/m9.figshare.30732827 (Manjoro et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1: Model comparison for error distribution selection where the asterisk (*) indicates the selected model.

Table S2.1: Effect of light condition on detection rate (fixed effects).

Table S2.2: Effect of light condition on detection rate (random effects).

Table S3.1: Secondary model: light condition with RH covariate (fixed effects).

Table S3.2: Secondary model: light condition with RH covariate (random effects).

Table S4.1: Presence/absence model: binomial GLMM (fixed effects).

Table S4.2: Presence/absence model: binomial GLMM (random effects).

Table S5.1: Period-level predictions (predicted hourly detection rates).

Table S5.2: Period-level predictions (pairwise comparisons vs. night reference).

Table S5.3: Period-level predictions (random effects).

Table S6.1: Continuous light intensity model (fixed effects).

Table S6.2: Continuous light intensity model (random effects).

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