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Primum non nocere: Technologically advanced non-invasive pheromone traps for sustainable monitoring of the European threatened hermit beetles *Osmoderma barnabita / eremita* (Coleoptera: Scarabaeidae)

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A smart pheromone trap designed for the monitoring of *Osmoderma barnabita / eremita* has been successfully developed and tested*in situ*. The trap's design and operational principles allowa photo-recording of the capture moment and logging parameters of air temperature and humidity at the moment of capture. These dataare then seamlessly transmitted to a server via mobile network. The adaptability of environmental parameter recording allows customization to suit specific requirements of a given study. Rigorous testing of these traps within three Natura 2000 sites in Latvia in 2003has substantiated their robust performance and efficiency. Notably, the traps exhibit versatility and can be modified and tailored for monitoring various insect species, utilizing both pheromones and lures as attractants. This innovation holds promise for advancing ecological research and monitoring endeavours pertaining to diverse insect populations.

Key words: insect monitoring, cost efficiency, remote, smart, threatened species, innovative

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INTRODUCTION

Biodiversity is declining globally at an unprecedented rate (Butchart et al., 2010, Dirzo et al., 2014,Tittensor et al. 2014), with nearlyone million species of living organisms potentially threatened with extinction within the next few decades (IPBES, 2019) and populations of many species experiencingsignificant decline globally or regionally (Hochkirch et al., 2023 and references therein).The most recent study revealed that 24% of invertebrate species are threatened with extinction in Europe (Hochkirchet al.,2023). Along with the more noticeable forms of life such as plants, birds or mammals, the commonly neglected world of invertebrates unnoticeably faces the same challenges. Insects, a particularly diverse group of invertebrates and the world's most diverse groups of living organisms, are fundamental components of food webs in terrestrial and aquatic habitats and provide vital ecosystem services such as pollination, pest and plant control, recycling of biomass, and other (Daily, 1997, Losey and Vaughan, 2006, Schuldt and Assmann, 2010, Larsson, 2016 and references therein). However, our knowledge level of insect diversity, bionomy, behaviourand distribution remain poor not only in terms of potentially required conservation measures. Several important segments of global and national economy, such as forestry and agriculture, are seriously affected by lack ofthe adequatedata as well. Pest control and eradication of invasive alien species is becoming one of major topics of global and national concern (e.g., Poland et al., 2021, Brockerhoffet al., 2023). Every year, a large amount of funding is spenton pest surveillance, forecasting, and monitoring, as well as on reducing their negative impact on both economies and biodiversity. A reliable, simple, and affordable methods for prompt obtaining reliable data appear therefore crucial both to tackle the global biodiversity loss and reduce financial losses in certain economic sectors. Extinction risk assessments of biodiversity patterns at regionalor global scale are of particular importance to ensure the limited resources available for biodiversity conservation are distributed and spent effectively (Schuldt and Assmann, 2010 and references therein).

Monitoring of rare and threatened insects for conservation purposes has remained largely unexplored in spite of continuously growing interest in and demandfor biodiversity conservation. Systematic surveys of endangered insects based on wide spectrum ofcollectingmethods such as light traps, flight interception traps, pan traps, pitfall traps or even specifically trained dogs (Bouget et al., 2009, Jansson, 2009, Driscoll, 2010,Vrdoljakand Samways, 2012, Merckx and Slade, 2014, Mosconi et al., 2017) provide an overview of some general trends in monitoring threatened insectspecies, but their ability to provide fine-grained information about individual species promptly is considered limited (Driscoll, 2010) and often require intense efforts that combine several methods (Ranius and Jansson, 2002). Monitoring insects using pheromone-baited traps could greatly facilitate data availability on occurrence and abundance of many endangered insect species, in particular, saproxylic beetles (Tolasch et al., 2007, Larsson et al., 2009, Barbour et al., 2011, Ray et al., 2012, Svensson et al., 2012).

Advanced technology of an information age has the potential to change the game for conservationists by allowing continuous monitoring the pulse of the natural world with reduced interaction required from involved staff. The role that computational tools and technology starting to play in assistance to model, monitor, and respond to the challenges of global biodiversity loss is already extensive (Joppa, 2015). Digital technology is nothing new in environmental sciences as it possessesan information management and analytical power. The establishment of sub-disciplines such as ecological modelling and bioinformatics, Geographic Information Systems – GIS, testifies to this (Maffey et al., 2015). The increasingly widespread availability and use of information and communication technologies (ICT) such as sensor networks, wireless communication devices, internet, big data management and simulation software, have facilitated developing technologically advanced subautonomous to autonomous remote insect surveillance devices which nowadays are most frequently used in pest monitoring (Holguin et al., 2010, Bjerge et al., 2020, Cardim Ferreira Lima et al., 2020, Ramalingam et al., 2020, Preti et al., 2021). Ongoing miniaturisation of technology allows for tracking of really small animals, right down to insects (Lihoreau et al., 2012), and integration of different types of sensors should allow registering different exogenous environmental variables (e.g., ambient temperature and light, relative humidity etc.) and other data, that furtherallow users to make rapid and better-informed inferences (Wall et al., 2014). When carefully used, smart solutions have several considerable advantages that can make the monitoring more efficient, less invasive, like fast data transmittingand ability to turn data into information without human participation, therefore, more cost-efficient since fewer man-daysand energy like fuel are spent on monitoring, and provide greater flexibility regarding the monitoring object.

Saproxylic beetles are insects that depend on decaying and dead wood for at least a part of their lifecycle, and play important ecological roles in habitats, taking part in decomposition processes and the recycling of nutrients (Speight, 1989, Alexander, 2008, Stokland et al., 2012). In Europe, there are 58 families of beetles (Coleoptera) with about 29 000 species (Audisio et al., 2015). The exact number of saproxylic species is unknown for Europe but is considered over 4 000 species (Cálix et al., 2018). Overall, 17.9% and 21.7% of saproxylic beetle species are considered threatened in Europe and in the EU 27/28, respectively (Cálix et al., 2018).

Hermit beetles of the genus *Osmoderma* Le Peletierand Audinet-Serville, 1828 are mid-sized scarabs that are confined to the Holarctic realm. The genus comprises 15 extant species and subspecies (Tauzin, 1994a and b, Smetana 2006, Audisio et al., 2007, 2009, Bezborodov, 2016, Bezděk, 2016). The genus *Osmoderma* in Europe is represented by five species – *O. eremita* (Scopoli, 1763) with the occurrence in most of central and western Europe, the Sicilian endemic *O. cristinae* Sparacio, 1994 and the southern Italian endemic *O. italicum* Sparacio, 2001, the predominantly Eastern European *O. barnabita* Motschulsky, 1845, and *O. lassallei* Baraud and Tauzin, 1991, an endemic in northern Greece and European Turkey (Audisio et al., 2007, 2009).

Osmoderma species are typical representatives of old-growth temperate forests and traditional wooded pastureland bound to veteran hollow deciduous trees, and all *Osmoderma* species significantly declined in the last decades due to the loss in extent and quality of the habitat loss (Eliasson and Nilson, 2002, Maurizi et al., 2017). At least in Central and Eastern Europe, hermit beetles' survival now relieson artificial habitats outside of forests, such as urban parks, wooded grasslands, old orchards, and old avenues (Vignon et al., 2004, Ranius et al., 2005, Oleksa et al., 2007, Carpaneto et al., 2010, Telnov and Matrozis, 2012).

During the last decades, the O*smoderma barnabita* / *eremita* species complex has emerged as a major model for ecological research on insectsassociated with hollow deciduous trees in Europe (Ranius, 2002, Ranius et al., 2005). As a threatened, umbrella species indicating the presence of a species-rich saproxylic fauna, *O.eremita* is listed as a priority species in Annex IV of the EU's Habitat Directive (Anonymous, 1992). *Osmoderma* beetles are demanding regarding the quality and availability of habitat, therefore preserving hermit beetle populations always results inthe "automatic" safeguarding numerous other organisms bound to veteran deciduous trees (Caro and O'Doherty, 1999, Simberloff, 1998) and whose requirementscan be used to guide management activities suitable for a larger group of ecologically similar species, for which there might beless information available (Breckheimeret al., 2014). Thereby it is not surprisingly that *Osmoderma* species has received much attention in the last decadesas a key species-group for conservation of entire invertebrate and vertebrate communities associated with hollow trees in Europe (Ranius et al., 2005 and references therein), which, in turn, facilitated demand for advanced and more efficient monitoring tools. As for a species with specific habitat requirements, specific approach is required for monitoring *Osmoderma* beetles. Furthermore, adult hermit beetles usually live for a maximum of 30 days (Ranius et al., 2005) and active only from July till September (depending on a geographic area), after which the adults die and disappear, so there is short time period available for monitoring. Since *Osmoderma* beetles spend most of their life time in tree hollows in larval stages and adult forms can be observed outside host tree hollow for just a short time period, it makes it challenging to identify presence of adults and determine size of local populations. During about two decades of research, different passive approaches for capturing saproxylic beetles, including *Osmoderma*, have been tested and adapted (e.g. window traps, pitfall traps, aluminium foil traps, wood mould sampling, "osmo dog" etc.) and though every method has its pros and cons, they have proven to be either not selective enough for monitoring a single species, invasive (adults often die in traps before being counted and released), too uncertain (e.g. identifying a species and estimating the population by presence of body parts in wood mould samples), or too demanding regarding the characteristics of the sample tree (hollow has to be wide enough, situated not too high from the ground, wood mould surface not too far from hollow openingto be accessible etc.) (Ranius, 2002). Although pitfall trapping has been widely recognised as more efficient method for capturing adult specimens of wood mould inhabiting species (Peuhuet al., 2019, Ranius and Jansson, 2002), still the selectivity of this method is low and, similarly to other passive methods, is unnecessary lethal for specimens of both target and non-target species. Though all a fore mentioned methods are relatively cheap (although not energy efficient since theyrequire frequent visits to control installed traps), simple and provides information about the general trends, they fall short when there is need to acquire specific data on individual species at specific site.

As a gamechanger, during the last decade, monitoring with pheromone traps have become a "new classic" method in research of insect biodiversity and conservation for its ability to attract adult specimens of a single, targeted species, and therefore being a sensitive and selective monitoring tool.

Pheromone traps have proven to be the most common and most efficient tool for research of various insect species (for instance, forestry "pests"), population monitoring and conservation of rare and threatened species, also being useful for identifying biodiversity hotspots and general changes in biodiversity in response to landscape, climatic, or other environmental changes (Larsson, 2016). Almost all available pheromones of explicit conservation interest appear female-produced sex attractant pheromones, including those of the Spanish moon moth *Graellsia isabellae* (Graells, 1849) (Miller et al., 2010) and other moths (Gago et al., 2013, Yan et al., 2015), the rust red click beetle *Elater ferrugineus* Linnaeus, 1758 (Svensson et al., 2012, Tolasch et al., 2007), and related species (Konig et al., 2016, Tolasch et al., 2013), and longhorn beetles of the genera *Prionus* Geoffroy, 1762 (Barbour et al., 2011), *Tragosoma* Audinet-Serville, 1832 (Ray et al., 2012), and *Desmocerus* Dejean, 1821 (Ray et al., 2014). The only exception so far is the male-produced sexual aggregation pheromones of scarab beetles in the genus *Osmoderma* (Larsson et al., 2003, Svensson et al., 2009, Zauli et al.,2014). Identifications of several other sexual aggregation pheromones of longhorn beetles of conservation concern are ongoing (for an overview of potentially interesting model genera see Hanks and Millar, 2016).

Osmoderma eremita was the first insect pheromone identified specifically as a tool for conservation, (R)-γ decalactone is the sex or aggregation pheromone of the *O. eremita* (Larsson et al., 2003). However, according to Larsson (2016), this pheromone represents the least efficient pheromone trapping system developed for conservation monitoring, and preferably should be used in combination with other methods. Since the ecological habits of the speciesas well as surrounding environment factors like weather conditions, temperature and moisture can often affect the fraction of the beetle population caught in pheromone traps, the results would be more trustworthy, if the presence/absence and dispersity of the specie would be evaluated in accordance with actual environment parameters.

MATERIAL AND METHODS

Smart trap design and operating principle

To increase the efficiency of monitoring and boost data accuracy, we significantly updated and improved a classic pheromone trap providing itwith several pre-defined functions foradditional functionality. For this purpose, a smart environment-monitoring systemwas designed, that aims to records environmentalvariablesuch as air temperature and humidity, as well as is capable for remote identification of a trapped object and loggingan exact trapping time. The system was additionally equipped with a data transmitter ensuring data capability and upload all collected data to a dedicated internet server, making all data accessible to researchers in real-time.

The electronic trap, designed for ecological or faunistic research, integrates several components to optimize its functionality and durability under various environmental conditions. The trap's structural design comprises a funnel, an insect storage compartment, and an electronics module, all fabricated using 3D printing technology from weather-proof materials. The design and material choice allows the device to operate in environments with ambient temperatures ranged -5 to+60ºC including under rain.

When lured insect specimen enters the funnel, it will fall down due to the gravity and slippery surface of funnel's walls. During the fall, an insect triggers light gate sensor located within the electronics module. Subsequent to the detection, the system activates its imaging component - a camera equipped with an infrared flash. This enables image capture of atrapped object regardless of ambient light conditions. Simultaneously, the trap's integrated external environmental sensors record surrounding air temperature and humidity, providing contextual data corresponding to the moment of capture.

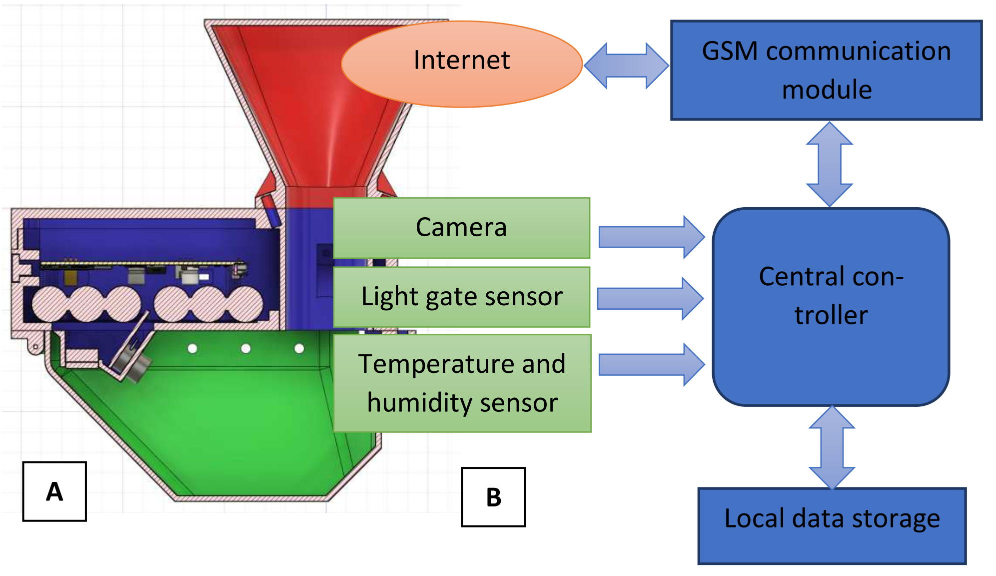

Fig.1. **A)** The structure of a smart trap. Red – funnel, blue – electronics compartment, green – insect storage compartment. The output of a funnel is aligned with cylindrical channel. The optical gate sensor is located inside a channel. **B)** The scheme of electronical systems of a trap and the flow of data.

The light sensor construction is demonstrated in Fig. 2. In the central cylindrical channel light beam emitted by the light source (A) will be discontinued by a falling object (insect specimen) which will result in loss of voltage generated by a light detector (B). Both light sensor and detector parts are indented deeply into walls of a channel in order to prevent contact with water droplets caused by rain or dew. In case of a continuous operation of a light source the capture (fall) of an insect is indistinguishable from short term changes in ambient lightning, therefore, integrated light source should operate in pulsed mode. In such case afall event can be triggered by absence of voltage in light detector during multiple pulses with subsequent recovery. It is essential to select a light pulse frequency that ensures an object disrupts the light path for a minimum of five consecutive pulses in order to ensure successful detection. Minimal viable light sensor pulse frequency is given by the equation.

$$f = \frac{\sqrt{50hg}}{l}$$

where f is the required pulse frequency, l is the shortest visible dimension of an object (insect), h is the height of a funnel, and g is free fall acceleration. Is case of *O. barnabitа*and given funnel design, the minimum viable frequency is calculated 95.8 Hz;

therefore, an operating pulse frequency of 100 Hz was selected.

The operating principle of a smart traps is easily adjustable. The selected construction allows the trap to be modified according to a specific object (e.g., various insect species) and used with different types of baits, pheromones, kairomones and other possible attractants, as well as adjusting the diameter of light gate sensor opening and pulse frequency in accordance with object's dimensions. Therefore, we believe that with the right modifications, smart traps can be used for research and monitoring of many different species.

Testing of traps in the field

Trap testing was carried out systematically during the 2023 field season covering the period from late May to early August. This assessment focused on three Natura 2000 sites in Latvia – Ziemeļgauja (LV0600700), Lubāna mitrājs (LV0536600) and Ances purvi un meži (LV0523400), where *O. barnabita* occurs. A group of five smart traps was carefully deployed per each of the mentioned Natura 2000 sites. In addition, 28 classic pheromone traps were set in each Natura 2000 site. This approach was undertaken to assess the efficiency and reliability of smart traps.

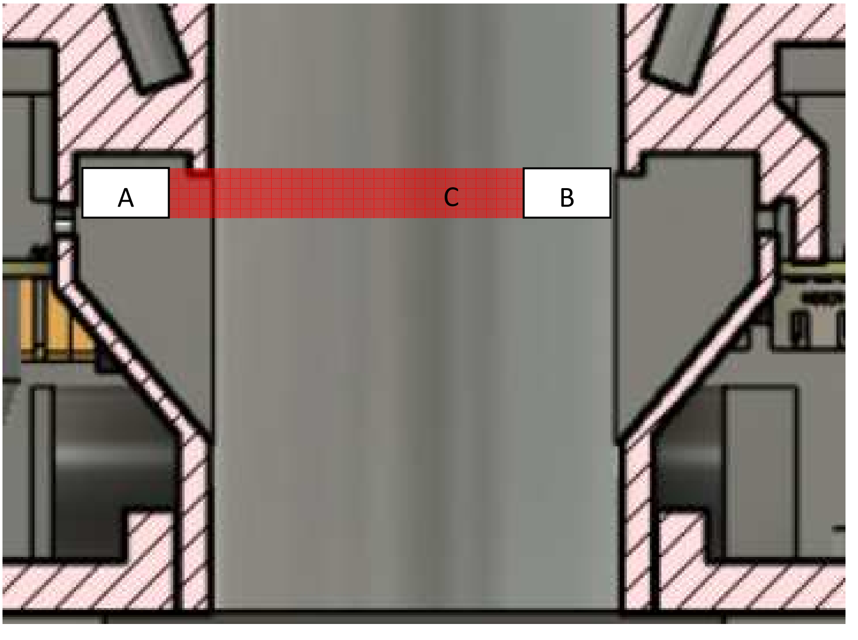

Fig. 2. Cross-section of alight gate sensor in a funnel of a smart trap. Rectangle **A** – location of light source, rectangle **B** – location of light detector, red line **C** – light beam.

RESULTS

A total of 15 smart traps and 84 classic pheromone traps were installed in three Natura 2000 sites for the exposition period of 72 days, totalling 1080 trap-days. A total of 73 hermit beetle individuals were captured using the smart traps and 727 - with classic pheromone traps. The findings of this study indicate that the efficacy of smart traps is statistically indistinguishable from that of conventional traps. Throughout the entire study duration, the traps consistently gathered and transmitted data on air temperature and humidity. This recorded dataset aligned closely with actual weather conditions, validated through comparison with data obtained from the nearest meteorological stations. The data also contained accurate time stamps and information on environmental conditions for each hermit beetle capture, providing valuable insights into the activity patterns and bionomy of *O.barnabita*. Notably, twelve traps continuously transmitted data including environmental parameters and visual records of captured individuals. In three cases, data transmission was intermittent due to suboptimal mobile network coverage, but all observation data were carefully stored on a micro-SD card inside each of the traps ensuring availability of backup data in case of network interruptions. On average, captured and falling insects triggered light gate sensor for 34 ms, which with pulse frequency of 100 Hzappeared sufficient for reliable detection of aninsect. Figure 4 demonstrates typical light gate sensor response to a falling insect.

By utilization of specialised low power components, the smart trap was optimized for a minimal possible energy consumption:average sleep mode current with active light gate sensor of 1.5 mA was achieved, with the total daily energy consumption of 173 mAh and this includes energy required for data transmission. The maximal single charge runtime of 4 months with six 18650 type lithium-ion cells was achieved, which is crucial inreducing general maintenance requirements for a smart trap.

Fig. 3. Smart trap placed in a monitoring plot in Lubāna mitrājs reserve.

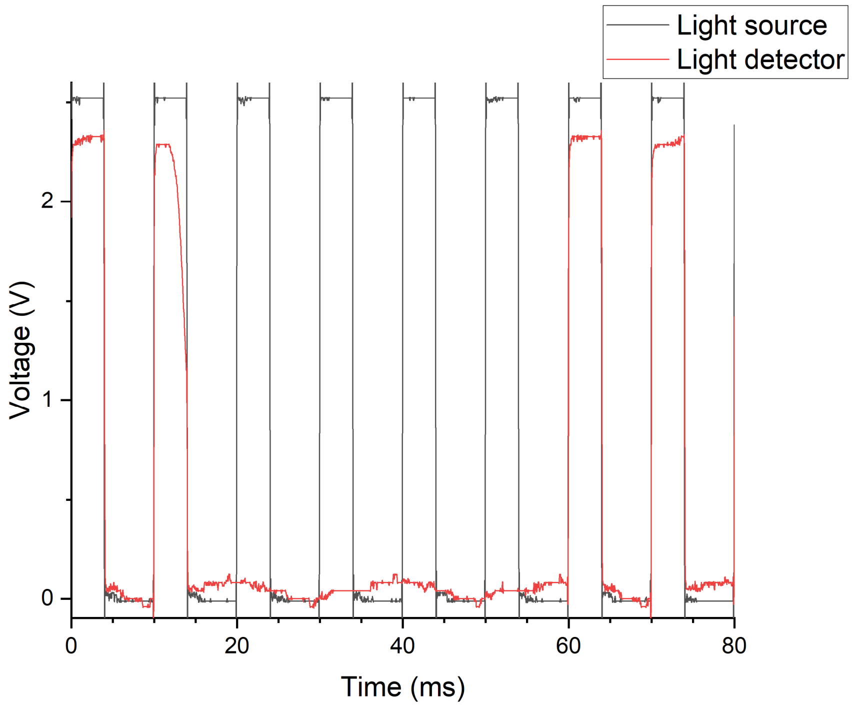

Fig.4. Applied light source voltage and light detector output voltage during insect-fall event. Tapered edge of light detector pulse at 15 ms indicates the insect starting to shade the light path of a gate sensor. The light path is completely discontinued for subsequent 4 pulses, with complete recovery of the pulse pattern afterwards.

DISCUSSION

The implication of real-time trap state monitoring (Figs. 5, 6) coupled with reasonably long single-charge lifetime allowed our research group to achieve a significant reduction in the duration and frequency of field trips and man-hours per installed smart trap compared to a classic pheromone trap and made revisiting only the traps with captured insect specimens (to measure and release them) possible thus reducing the costs of the research. While generally requiring less maintenance time, some amount of field work still remains necessary in order to manually release trapped specimens. Enhancements in trap design and functionality hold the potential to substantially decrease monitoring expenses while contemporaneouslyincreasing efficiency of monitoring process. Prospective challenges involve the incorporation of an automated specimen marking and a marker recognition system, alongside with constructing a remote release system for captured individuals. The successful implementation of these improvementsnecessitateadditional research on individual dispersion, behaviour, longevity, and other pertinent aspects.

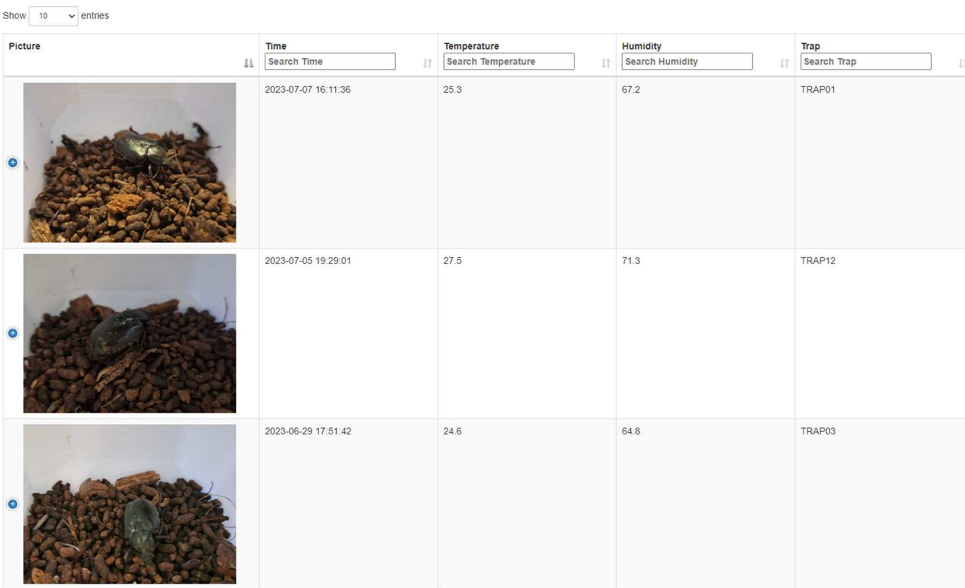

Fig.5. A screenshot of a real-time trap-monitoring web interface with threelatest successful insect captures shown.

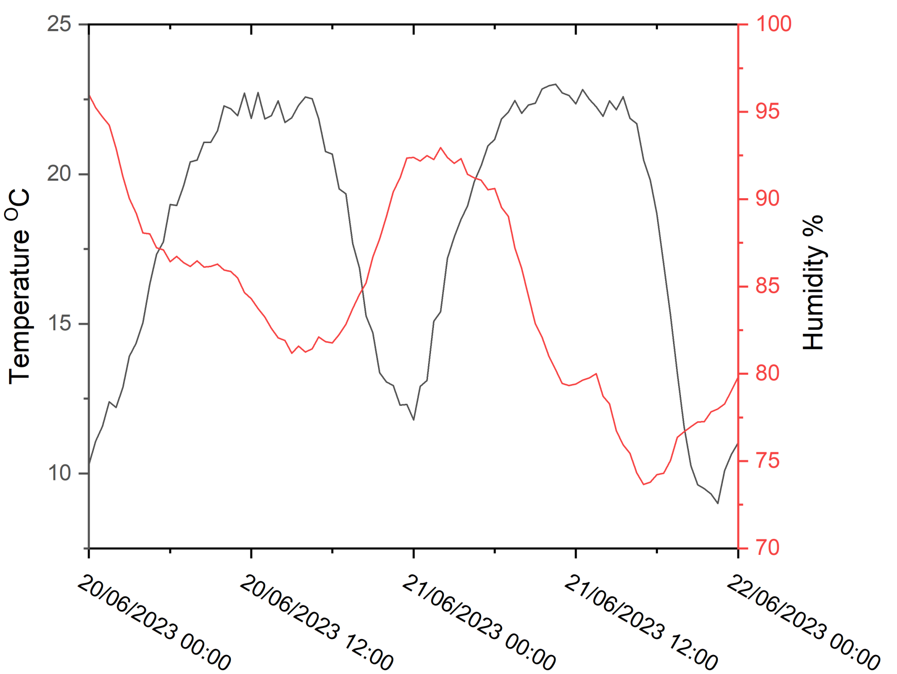

Fig.6. An example chart of temperature and humidity data captured by trap's externalsensors.

While the trap design and functionality mark a significant advancement and innovation in ecological monitoring tools, certain limitations were also documented. The light gate sensor requires thoughtful selection of installation position, as well as funnel lid design should be improved in order to minimize the amount of natural debris falling through a funnel and false-activating a light gatesensor. The implemented design of the light gate sensor appearedinoperable during heavy rain conditions, since water flowing inside funnel is disrupting the light beam (however, activity of *Osmoderma* adults under heavy rain conditions is usually suspended as well). While the GSM network coverage in our study region was generally suitable, a limited number of traps were unable to establish connection with the server, thus requiring in-person visits to manually obtain saveddata. One possible further improvement to the system may be equipping traps with a satellite communication moduleand providingmore efficientrainfall protection.

The integration of smart traps to a monitoring process and methodology of protected beetle species represents a transformative leap forward in ecological research and conservation. Through a survey of recent studies, exemplified by the success of smart traps in detection of alien longhorn and bark beetles (Rassati et al., 2016) and various crop insect pests (Chen et al., 2023, Schrader et al., 2022, Suto 2022, 2023), it became evident that these intelligent trapping technologies provide substantial advantages.

The precision in collecting data, capturing real-time behavioural patterns, and transmitting environmental parameters provide unparalleled insights into the ecology of protected beetles.

The inherent modular design of smart traps provides a remarkable degree of flexibility, allowing for easy reconfiguration or adaptation to accommodate different species of insects. This adaptability is achieved through the adjustment of changes to the trap body and the incorporation of various environmental sensors. Such versatility substantially enhances the practicality of these traps, making them well-suited for a wide array of environmental studies across diverse ecological contexts.

While acknowledging challenges such as initial costs, the long-term benefits of employing smart traps significantly outweigh these challenges. The potential for continued refinement in trap design, expansion to monitor a broader range of species, and applications in diverse ecosystems underscores the promising future of smart traps in biodiversity monitoring.

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