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RESEARCH

Developing a nest box data logger for dormice: a case study of wild hazel dormice (*Muscardinus avellanarius*)

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Abstract

We present the design and application of the Dormouse Data Logger Generation 3 (DDL3), a novel, programmable and modular monitoring system integrated into a standard nest box for dormice. The logger is recording the nest chamber through various sensors. Incorporating multiple power-saving strategies, the system achieved battery runtimes of over one month, enabling extended monitoring with minimal disturbance. It has been continuously deployed in the field since 2023, demonstrating stable operation under variable environmental conditions. The data collected from a single nest box during the 2024 season are presented here. The DDL3 provided a reliable record of post-hibernation activity in a nest box and enabled detection of seasonal fluctuations in body mass of hazel dormice. Camera, scale and motion-sensing functions supported recognition of torpor events. In addition, the camera recorded behavioural data, documenting cooperative nest construction and rearing offspring. These capabilities enable continuous, non-invasive monitoring of the seasonal dynamics of hazel dormouse behaviour, including pre-hibernation activity. This demonstrates the DDL3's suitability for high-resolution wildlife monitoring and conservation studies.

Keywords Nest box · Data logger · Small mammal · Automated data collection · Hazel dormouse · Arduino

Introduction

Small mammals such as the hazel dormouse (*Muscardinus avellanarius*) serve as a critical component of terrestrial ecological networks, contributing substantially to ecosystem stability and trophic dynamics (Fedyń et al. 2021). Although the hazel dormouse is an omnivore, it exhibits a broad herbivorous dietary spectrum and acts as a seed disperser (Juškaitis and Baltrūnaitė 2013). Moreover, this rodent was recorded in the diet of at least 54 predator species (Juškaitis 2023).

Structurally complex early-successional woodland understories, with high plant species diversity, provide essential food resources for hazel dormice and suitable nesting sites (Combe et al. 2023). Consequently, hazel dormice show a strong preference for these types of woodland habitats, where they achieve greater reproductive success (Goodwin et al. 2018). As a result, the species is widely considered a reliable indicator of habitat quality and successional processes within these environments (Morris 2003; Ramakers et al. 2014; Mortensen et al. 2022; Scopes et al. 2024).

In Germany, hazel dormice usually hibernate from late October to the end of April (Pretzlaff et al. 2021). Post-hibernation survival in hazel dormice is primarily determined by body mass prior to hibernation, which is strongly influenced by the availability of diverse and continuous food resources throughout the active season (Csorba 2003; Juškaitis 2007). However, survival is also linked to several additional factors, including individual age, the characteristics of their hibernation sites, and climatic conditions (Combe et al. 2023; Goodwin et al. 2018; Gubert et al. 2025).

Even though the hazel dormouse is considered a species of 'least concern' globally in the IUCN database, it is listed as 'threatened' in the red list report of Thuringia, Germany (von Knorre and Klaus 2021). Furthermore, the species is included in Annex IV of the EU Habitats Directive, which mandates strict protection, monitoring and habitat preservation (Council Directive 92/43/EEC 1992). Despite its ecological services and its legal protection across Europe, the hazel dormouse faces an increasing extinction risk thought

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to be driven by climate change and human-induced habitat destruction and degradation (Combe et al. 2023; Iannarilli et al. 2017).

Being a hibernating species with limited dispersal abilities in fragmented habitats and facing increasing fragmentation of suitable habitats, the threat to hazel dormouse survival is exacerbated. For instance, a study on population genetics in central Italy reported a loss of genetic diversity resulting from restricted dispersal caused by habitat fragmentation (Bani et al. 2017). A recent study on its population and distribution in the UK has revealed that the hazel dormouse population declined by over 70% within only two decades, from 1993 to 2014 (Godwin et al. 2018). This downward population trend has continued and reached nearly 80% decline by 2020 (Scopes et al. 2023). With an annual population decrease of about 6%, projections indicate the species could experience a decline of over 90% by 2034 in the UK (Goodwin et al. 2017; Scopes et al. 2023). Similarly, in Germany, where this species exhibits limited movement within fragmented landscapes, it may be vulnerable to comparable survival threats (Büchner 2008). Local-scale population decline of a species can serve as an early indicator of global decreasing population (Cowlishaw et al. 2009).

Accordingly, monitoring hazel dormouse habitats and populations is essential for formulating a conservation management strategy that complies with the EU Habitats Directive (Council Directive 92/43/EEC 1992). Gaining insights into the behaviour of this rodent would further strengthen conservation management efforts. However, studying these elusive animals remains challenging due to their nocturnality and preference for arboreal habitats (Bright and Morris 1996, Fedyń et al. 2021).

Tree cavities and holes are essential for hazel dormice and other small arboreal mammals (Fedyń et al. 2021). Because of high intra- and inter-specific competition for safe nesting places, hazel dormice readily accept nest boxes, which serve as artificial replacements for natural tree hollows (Fedyń et al. 2021). As a result, dormouse nest boxes have been widely adopted as effective tools for research and conservation efforts (Morris et al. 1990).

In conventional nest box surveys, animal disturbance is unavoidable (Brito Vera et al. 2022). Checking the boxes and handling the animals causes stress, increases their energy expenditure and may lead to nest abandonment (Loretto and Vieira 2011). Therefore, surveys are generally conducted no more than once a month, which limits the quality and quantity of the collected data. In addition, monitoring animal activity within the box remains challenging. However, constant advancements in technology, such as power-efficient microcontrollers and batteries with high energy density, are helping to integrate autonomous data collection into small mammal research, which is enhancing data quality while reducing disturbances to the animals (Bosch et al. 2015; Büchner et al. 2022). Despite a recent increase in research on dormouse species, many aspects of their biology and behaviour are still poorly understood.

This study presents the integration of a data logger into a nest box, providing an efficient means to collect comprehensive data on dormice while minimising disturbance to their natural behaviour. The novel Dormouse Data Logger Generation 3 (DDL3) provides detailed insights into dormouse behaviour, reproductive cycles, torpor and hibernation patterns, as well as habitat preferences. As an automated device, the DDL3 reduces human intervention and is cost-effective, with total material expenses of less than €200 per unit as of 2025. The data logger has evolved through three generations over four years of development. Once finalised, assembling a complete DDL3 unit - including preparation and production of all components - requires approximately three to five working days for a single person.

Materials and methods

Study area

The study site was located within the "Spitzenberg-Schießplatz Rothenstein Borntal" (50° 51′ N, 11° 34′ E) nature reserve, situated in the district of Jena, Thuringia, Germany. The reserve is managed primarily for the conservation of a structurally complex and species-diverse forest ecosystem with open habitats, especially species-rich calcareous grasslands dominated by orchids (Wenzel Holm et al. 2012). Jena experiences a warm temperate climate, characterised by an annual mean temperature of 10.3 °C, annual precipitation of 595 mm, and an average of 1,492 sunshine hours per year (Deutscher Wetterdienst/SKlima 2025). Tree species within the nature reserve are dominated by European red pine (*Pinus sylvestris*), with an admixture of European ash (*Fraxinus excelsior*) and European beech (*Fagus sylvatica*). The shrub layer in the area is predominantly composed of common hazel (*Corylus avellana*), European cornel (*Cornus mas*), and European fly honeysuckle (*Lonicera xylosteum*). In total 20 nest box data loggers have been deployed in the survey area. For this study, we present a nest box logger with an ID of B7, which was installed on a southern-exposed slope of the study area at 274 m elevation and attached to a small beech tree with a diameter at breast height of 13 cm (Fig. 1).

Fig. 1 Dormouse Data Logger Generation 3 (DDL3) labelled with ID B7 attached to a beech tree in the survey area of the nature reserve "Spitzenberg-Schießplatz Rothenstein Borntal" in Jena, Germany

Design of the data logger-equipped nest box

Nest box specifications

The nest box was constructed from rough-sawn timber, with the entrance hole orientated towards the tree trunk. The top and base of the nest box were constructed from plywood of 40 mm and 23 mm in thickness, respectively, providing structural stability and resistance to warping. The external dimensions of the nest box measured 150 × 150 × 290 mm (length x width x height), while the internal dimensions were 104 × 104 × 217 mm. A gap between the weighing pan and the inner walls of the nest box was maintained to ensure correct weight measurements. Therefore, the weighing pan, which also functions as the nest chamber, was designed with dimensions of 96 × 96 × 96 mm. The functional entrance opening, through which dormice can enter and exit, measures 23 × 30 mm (height x width). Design specifications followed established recommendations for dormouse nest boxes: Lang et al. (2022) employed nest boxes measuring 95 × 95 mm with a 25 mm entrance diameter to minimise access by larger competitors and predators. Besides, hazel dormice tend to prefer larger 80 × 80 mm internal space to build their nests when presented with options from 50 × 50 mm, 60 × 60 mm, 70 × 70 mm and 80 × 80 mm (Heberer et al. 2018). A reduction of the entrance diameter of the nest box below 22 mm is not recommended, as it may hinder access for well-fattened hazel dormice during the pre-hibernation weight gain period, while potential nest box competitors, such as the yellow-necked mouse (*Apodemus flavicollis*) and wood mouse (*Apodemus sylvaticus*), will likely still be able to enter (Verbeylen 2017).

Features of the dormouse data logger generation 3

The DDL3 comprises a main control unit, an entrance sensor, and a weighing pan connected to a load cell (Fig. 2). A load cell is a technical device that converts force into an electrical signal via strain gauges and can therefore be used to measure weights (Deutsches Institut für Normung e. V. 2018).

Access to the interface, battery compartment, and micro-SD card is provided from the top of the unit, eliminating the need to open the nest chamber and thereby minimising disturbance to the animals (Fig. 3b).

The plastic parts of the DDL3, like the logger housing and weighing pan, were designed using Autodesk Fusion 360 (Autodesk Inc. 2024b) and subsequently 3D printed, utilising PrusaSlicer software (Prusa Research a.s. 2024). Components were printed with GreenTEC Pro filament, a food-safe material composed entirely of renewable resources (FD3D GmbH 2025). To facilitate the access and egress of hazel dormice, small ledges were incorporated into the walls of the weighing pan and on each side of the entrance. Additionally, drainage outlets were positioned at each corner of the weighing pan to allow water runoff and prevent accumulation (Fig. 4).

Electronic components

Electronic components were carefully selected based on their specifications (Table 1). They were assembled using a custom-designed printed circuit board (PCB), developed based on the schematics of the "Mighty Mini 1284P" (Christensen 2014). Modifications to the "Mighty Mini 1284P" power supply were made to accommodate the integration of various connected modules. Two separate voltage regulators (MCP1700) provided power to the board, one for the microcontroller chip and one for the peripheral circuitry (Atmel Corporation 2016). For the PCB creation, the software Autodesk Eagle was used (Autodesk Inc. 2024a). The PCB was manufactured at Aisler (Aisler B.V. 2025). Surface mount devices (SMD) were then manually positioned with tweezers and soldered using a reflow oven "Reflow-Kit V3 Basic" (Beta Layout 2025). The microcontroller was programmed using the Arduino Integrated Development Environment (Arduino 2021).

The DDL3 was designed with a modular architecture, both in hardware and software, to provide flexibility for a wide range of research applications. It offers connections for both common sensor interfaces, Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I2C), allowing the use of a wide palette of sensors.

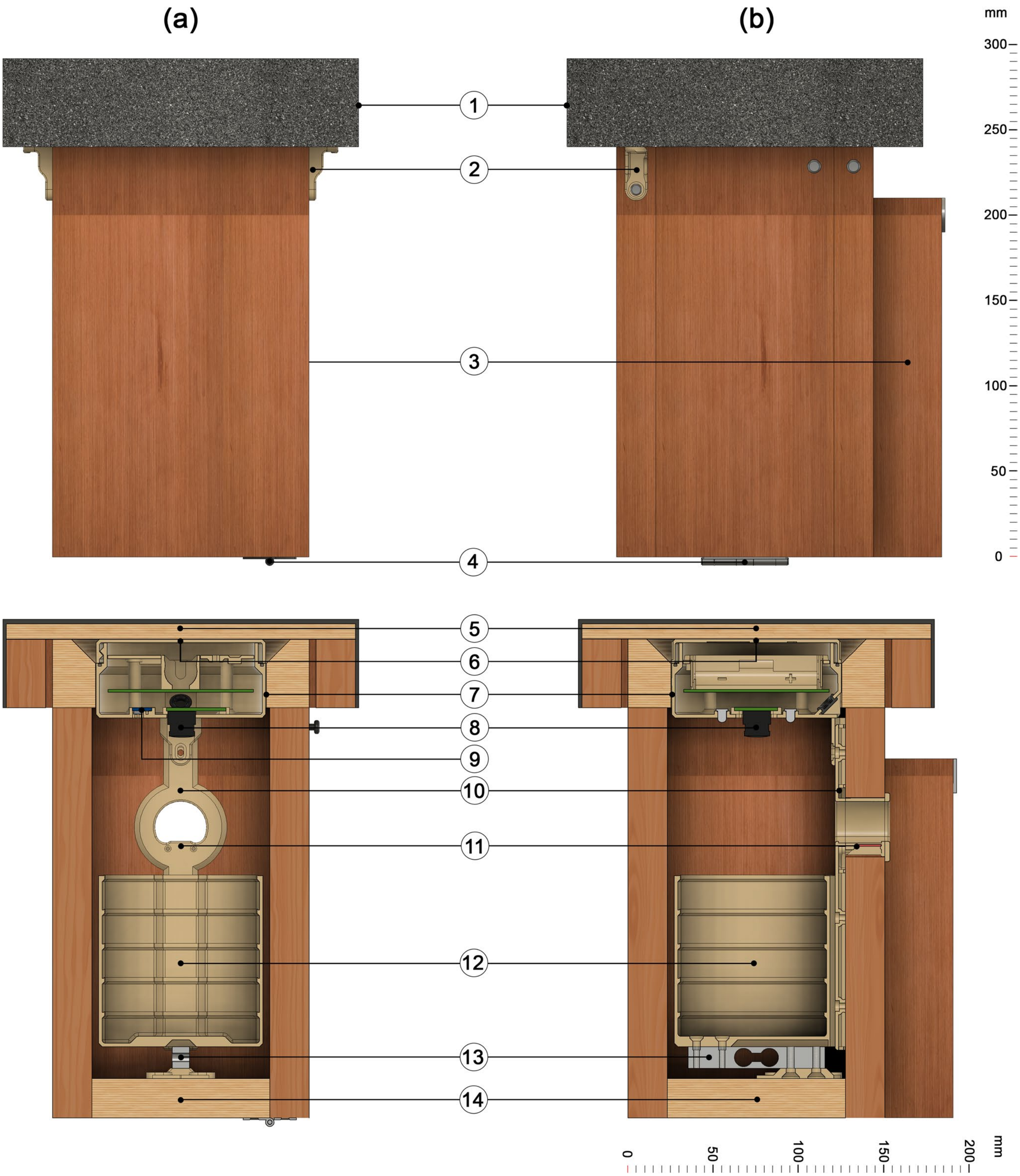

Fig. 2 Dormouse Data Logger Generation 3 (DDL3) in **(a)** back view, **(b)** side view, **1** – magnetic roof, **2** – retaining clip, **3** – spacer for tree trunk, **4** – side door hinge, **5** – lid (plywood), **6** – screw-on lid (plastic), **7** – main control unit, **8** – camera with infrared LED, **9** – temperature/humidity sensor, **10** – cable cover, **11** – entrance sensor, **12** – weighing pan, **13** – load cell, **14** - base (plywood)

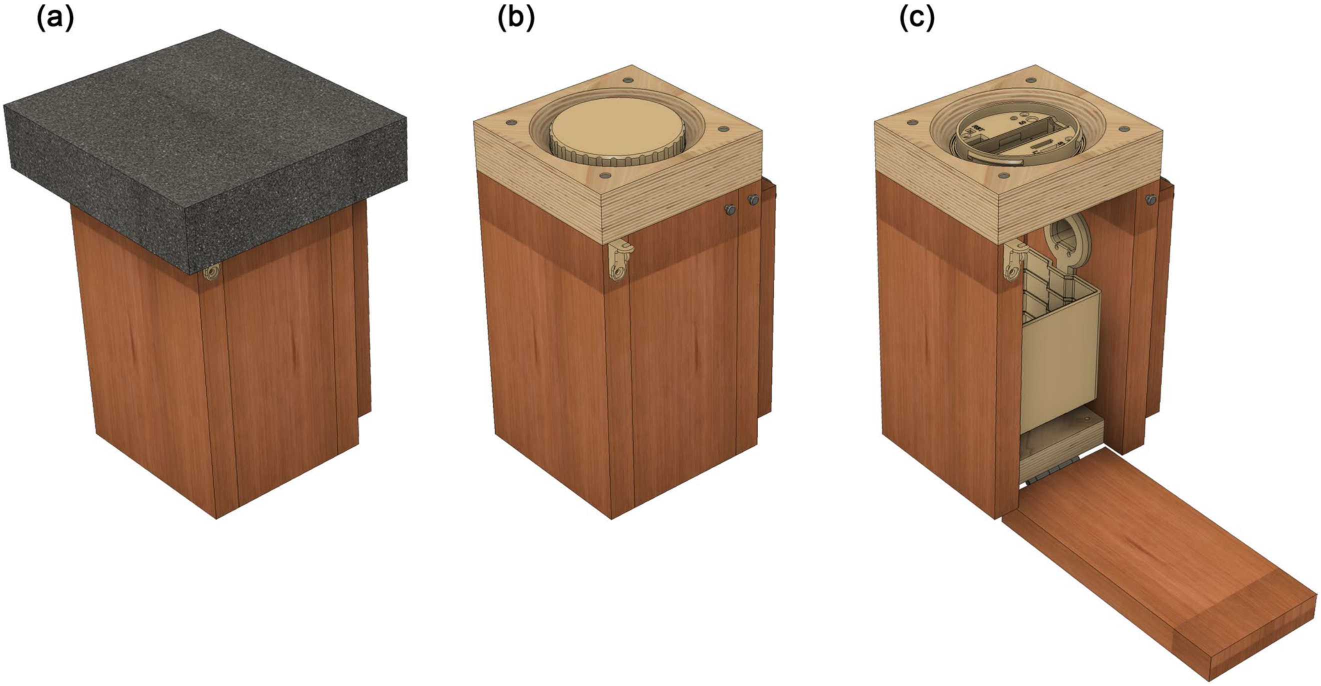

Fig. 3 Dormouse Data Logger Generation 3 (DDL3) as seen from **(a)** the outside **(b)** with magnetic roof removed **(c)** without roof and screw-on lid; the side door is opened to gain access to the nest chamber for manual inspection

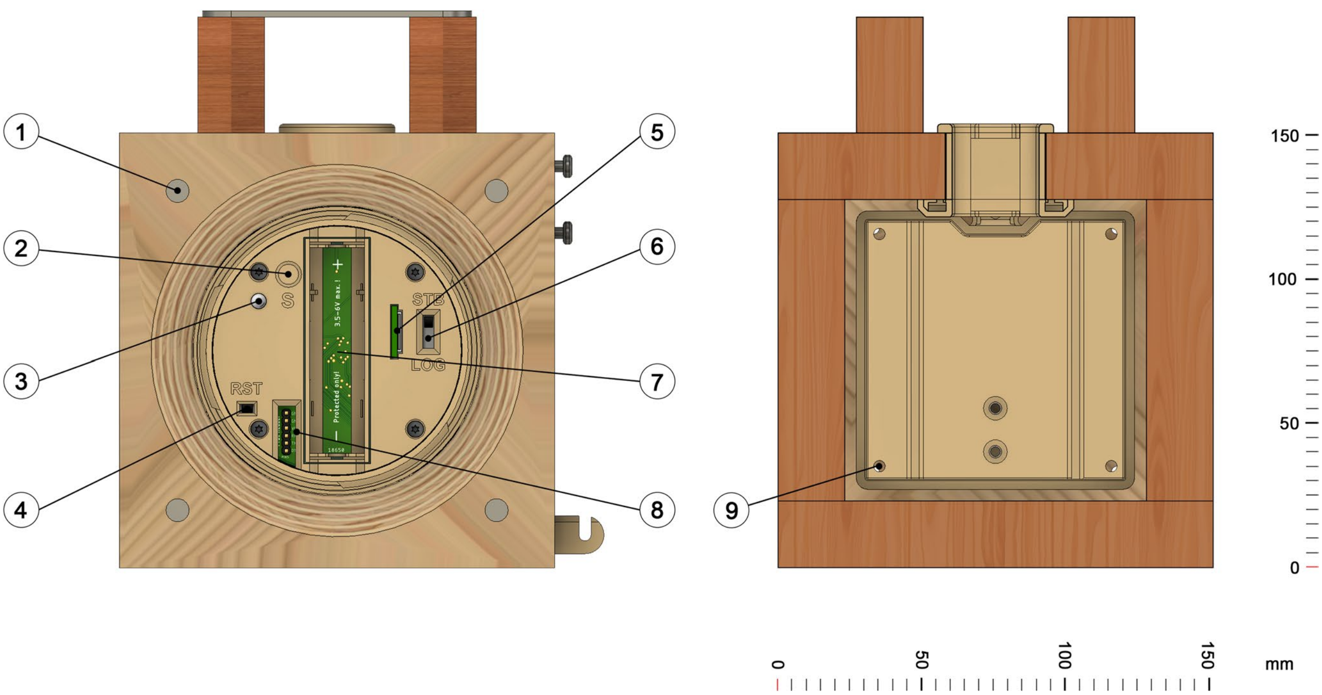

Fig. 4 Dormouse Data Logger Generation 3 (DDL3) user interface on the left and top-to-bottom cross section on the right, **1** - magnet, **2** – status button, **3** – status RGB LED, **4** – reset button, **5** – micro-SD slot, **6** – standby switch, **7** – battery compartment, **8** – FTDI port, **9** – drainage outlet

Power was supplied by a single 18650 lithium-ion battery equipped with an integrated protection circuit. Battery voltage was continuously monitored, and data logging was terminated once the voltage dropped to 3,500 mV to prevent system instability. To minimise energy consumption, the processor remained in deep-sleep mode for most of the operational period, with non-essential modules powered down. Specifically, power to the camera, temperature/humidity sensor, load cell amplifier, SD card and clock was removed. A backup battery within the clock module

Table 1 Electric components of the dormouse data logger generation 3 (DDL3)

Component	Description
Processor	ATmega1284p AU, 8 MHz @ 3.3 V, 8-bit, 128 kB Flash
Clock	Adafruit DS3231, ±2ppm accuracy from 0 °C to +40 °C
Voltage regulator	2x MCP1700T-3302E/TT, 3.3 V, 250 mA, 4 µA quiescent current
Entrance sensor	TTP223 touch sensor module, capacitive
Temperature and humidity sensor	Sensirion SHT-31, ±0.3 °C, ±2% RH
Camera	Arducam Mini 2MP Plus (OV2640 image sensor) with 1.8 mm VBESTLIFE CCTV Lens, 170°
IR illumination	2×940 nm Kingbright IR LED 5 mm (WP7113F3C, manually diffused)
Scale	Load cell Sauter CK 1-0P1 (1,000 g) connected to Sparkfun HX711 load cell amplifier
Battery	1x protected KeepPower 18650 (Li-Ion, 3,500 mAh)
Memory	Transcend micro SD 4GB HC

provided the power needed for timekeeping. Power to the entrance sensor and interface remained active, allowing the logger to respond to external interrupts.

Specific events, such as the initiation of a new sampling interval or the detection of animal activity at the logger entrance, acted as triggers to activate the system. It was anticipated that under these conditions the system could operate autonomously for over two months; however, batteries were replaced on a monthly basis to maintain a safety margin.

Data logging and the user interface

The DDL3 records several variables, including the number of animal passages through the entrance hole (activity), the weight of an animal upon entering, total nest weight, and the temperature and humidity inside the nest box, measured at regular 30-minute intervals. Between intervals when the SD card is powered down, activity data is saved in the non-volatile EEPROM (electrically erasable programmable read-only memory) of the chip to reduce energy consumption.

At the end of every interval, all variables are saved in .csv format on a micro-SD card inserted into a slot located at the top of the unit (Fig. 4). Each recording session generates a new .csv file, named according to the date and time of initiation. All timestamps are recorded in European Summer Time, with the transition to wintertime disregarded for practical purposes. Data retrieval occurred once per month together with the battery replacement.

To access the logger housing, the plywood cover (Fig. 3a) must first be removed. This reveals a plastic lid beneath (Fig. 3b), which, once unscrewed, provides access to the interface (Fig. 3c). To prevent data corruption during SD card removal, the logger can be manually switched to standby mode using a slide switch. The current operation mode of the logger is indicated by a single status RGB LED (Fig. 4), which blinks yellow during standby mode and green once to indicate logging has started. The interface and status RGB light are located beneath the wooden cover and underneath the plastic lid, making them invisible to both the animals inside the nest box and from the outside. During standby mode the SD card can be removed and the data copied to an external data storage such as a smartphone with a micro-SD adapter.

Additionally, upon pressing the status button, the current presence of an animal in the box or prior activation of the entrance sensor in the current recording session is signalled by blinking green, and the absence of the animal or lack of entrance sensor activation by blinking red. Subsequently the status RGB LED also serves as a 5-step battery level indicator, with one additional flash signalling a voltage step of ≤20%. A status button press therefore leads to two LED flashes, either green or red, followed by up to 5 flashes in blue. A reset button is available to restart the microcontroller. Software updates for the data logger are performed through the Future Technology Devices International (FTDI) port.

Data logger operational functions

Temperature and humidity monitoring within the nest box

Temperature and relative humidity inside the nest box were recorded using a Sensirion SHT-31 sensor (Fig. 2) positioned at the top of the nest box with an opening to the nest chamber. The sensor is pre-calibrated at the factory (Sensirion 2022).

Entrance sensor for activity detection

The DDL3 records activity at the nest box by counting the number of sensor passages through the entrance during each 30-minute interval. Entry of a dormouse into the nest box is initially detected by a small capacitive touch sensor (Fig. 2) positioned within 1 mm beneath the entrance surface. Though this sensor was originally designed for human touch detection, we tested it with *Apodemus* spp. and the hazel dormouse using video surveillance to assess its reliability prior to integration into the data logger, where it demonstrated strong potential. The sensor's low cost and minimal power consumption (1.5–7.5 µA) make it well-suited for this application (TT Electronics Plc 2007). To minimise energy consumption, the onboard resistor was desoldered, which deactivated the status LED of the touch sensor. The sensor was securely attached and sealed to the bottom of the entrance area using hot glue. The sensor recorded passages in real-time, incorporating a 5-second blocking time between triggers to avoid multiple recordings of an animal briefly resting at the entrance, thereby reducing false detections. The recorded activity data is saved to the SD at the end of each 30-minute interval.

Weight measurement

The load cell maximum capacity of 1 kg was chosen based on the expected animal weight and a safety margin for forces applied while removing an animal from the box or cleaning the weighing pan. Exceeding the maximum rated capacity of a load cell can cause irreversible damage due to plastic deformation. Prior to deploying the DDL3 to the survey area, a calibration of the load cell was performed through a routine using a 200 g reference weight placed on the empty weighing pan. The determined calibration values are then saved in EEPROM and used for weight measurements thereafter. Lighter calibration weights can lead to insufficient calibration and therefore inaccurate results. ISO 7500-1 demands a minimal calibration weight of 20% of the load cell capacity (Deutsches Institut für Normung e. V., 2018). However, the accuracy of the load cell measurements after calibration was also verified with test weights of 5, 10 and 20 g resembling the weight of a hazel dormouse.

Upon detection of an animal at the entrance, the DDL3 initiates a weighing routine if no weight already has been recorded during the current interval, beginning with the recording of a reference weight from the empty weighing pan. Over the subsequent 5 s, one weight measurement per second is documented while the animal is expected to be present on the pan. If any of these values exceeds the initial reference by at least 5 g, which corresponds to the expected minimum weight of a dormouse, the system proceeds to record seven additional weight measurements at 500-millisecond intervals. If the weight variation across these seven measurements remains within ± 5 g, the median of the values is calculated and stored as the weight of an animal. If the variation during the measurement process exceeds this threshold, the measurement is discarded. This protocol ensures that only a single individual, fully positioned on the weighing pan, is accurately recorded. The median is more robust to outliers compared to the mean and presents an actual measured data point. The weighing routine is triggered at each entrance event and is repeated once per 30-minute interval until an animal weight has been successfully registered. If no animal is detected during an interval, the data entry is marked as “NA”. In addition to activity-related measurements, the load cell also records the total weight on the weighing pan at every 30-minute interval, allowing the detection of gradual increases in weight due to the accumulation of nesting material. This continuous total weight measurement also helps to identify outliers in the animal weight, such as two individuals entering the nest box at the same time or a mother that would carry a young with her.

Interval-based weighing data were post-processed to minimise the influence of temperature dependency of the load cell. Due to the physical properties of the strain gauges, the load cell also registers forces resulting from thermal expansion, which are unrelated to actual changes in weight on the weighing pan. To correct for this effect, measurements from the load cell within ± 5 g of zero (interpreted as an empty nest box) were paired with corresponding temperature readings from a sensor located within the nest chamber. A linear regression model was fitted to these data to determine the slope and y-intercept, which were subsequently used to adjust the original weight measurements for temperature-induced variation. In addition to automated weight measurements, the animal weight was also determined manually by using a spring scale (Pesola LightLine 50 g, D = 0.5 g).

Photographic documentation of the animal

A camera was installed at the top of the nest box interior to capture images using infrared illumination. Illumination was provided by two LEDs emitting at 940 nm, a wavelength undetectable by mammals, thereby minimising disturbance (Newbold and King 2009). To ensure uniform lighting across the images, the LEDs were manually diffused using sandpaper prior to assembly.

Photographs were automatically taken at one-hour intervals and stored as .jpg files on the SD card. In addition, when an animal entered the nest box and a successful weight measurement was obtained, a photo was captured. Thus, image data were collected both at regular hourly intervals and opportunistically following animal detection and weighing events.

Data analysis

All analyses have been done with R Studio version 2025.05.0 Build 496 using R version 4.5.0. We used Spearman’s rank correlation coefficient with permutations ($n = 10{,}000$) from the R-package “coin” to analyse the correlation of nest box temperature and activity, thereby addressing zero-inflation in the activity data (Hothorn et al. 2008).

Results

Utilisation of the DDL3 by hazel dormice

The nest box was deployed from 29 February to 25 December 2024. Hazel dormice utilised the DDL3 system continuously from early March through late October for 233 days in total. Throughout this period, the DDL3 operated reliably without interruptions. Battery replacements were carried out six times between 29 February and 25 December. Following the final battery exchange on 15 October, the system remained operational for just over 70 days before reaching the predefined voltage threshold of 3,500 mV. Battery performance was influenced both by a higher level of animal activity at the nest box, which elevated power consumption, and by lower ambient temperature conditions, which can diminish the effective capacity of lithium-ion batteries (Zhang et al. 2003).

Recording temperature and humidity of the nest box

The maximum temperature within the nest box was recorded on 29 August 2024, reaching 30.89 °C, and the minimum temperature was observed on 1 December 2024, with a value of −2.28 °C. August was the warmest month, with a mean temperature of 20.54 ± 3.97 °C, while December was the coldest, averaging 3.16 ± 2.98 °C.

The highest relative humidity within the nest box was recorded on 3 August, reaching 99.99% RH. The lowest value, 36.33% RH, was measured on 8 April. October exhibited the highest average relative humidity at 89.29 ± 5.31%, whereas February was the driest month, with a mean relative humidity of 55.80 ± 2.58%.

Activity pattern monitoring

Monitoring of torpor events

On 2 March at 20:30, a dormouse (Dormouse 1) was recorded entering the box, with a measured body mass of 21.34 g. Dormouse 1 exhibited a partially missing tail (Fig. 5a).

From 12 March to 27 March 2024, Dormouse 1 spent the majority of its time in a state of torpor within the nest box. In addition, the individual utilised the box as a daytime refuge, with occupancy continuing until 1 April 2024, punctuated by occasional nocturnal excursions primarily between 20:00 and 23:00 (Fig. 6).

At this point its body mass had declined to 16.05 g. Over the 30-day monitoring period, Dormouse 1 experienced a net mass loss of −5.29 g (−24.79%), equivalent to an average of −0.18 g (−0.84%) of its initial body mass per day (Fig. 5a). During a manual inspection on 26 March, Dormouse 1 was found torpid within the nest box. It was carefully transferred to a weighing bag for body mass measurement. The manual

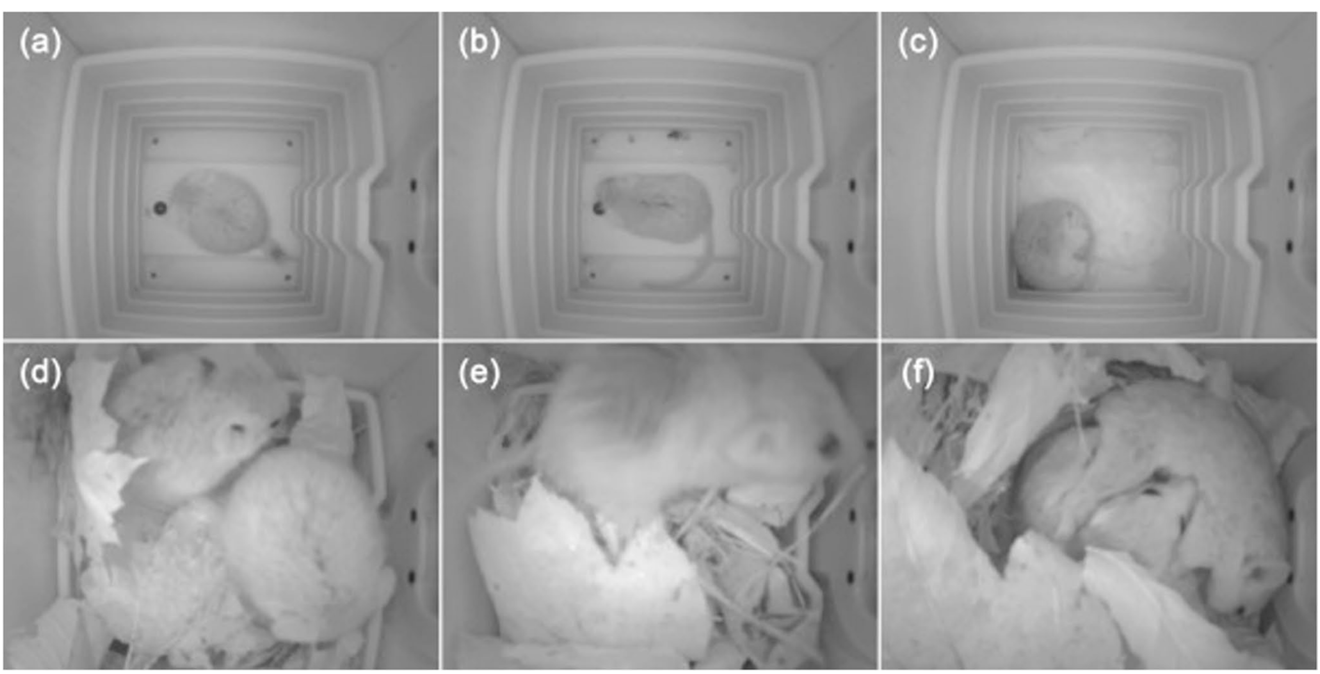

Fig. 5 Pictures from the Dormouse Data Logger Generation 3 (DDL3) nest box chamber taken in infrared light: **(a)** Dormouse 1 with a short tail on the 28 March, **(b)** a long-tailed dormouse on the 13 April, **(c)** beginning of nest construction on 14 April, **(d)** Dormouse 1 and another long-tailed dormouse together in the nest on 5 May, **(e)** a dormouse in the nest for a single day on 4 August, **(f)** a female dormouse nursing her young on the 4 September

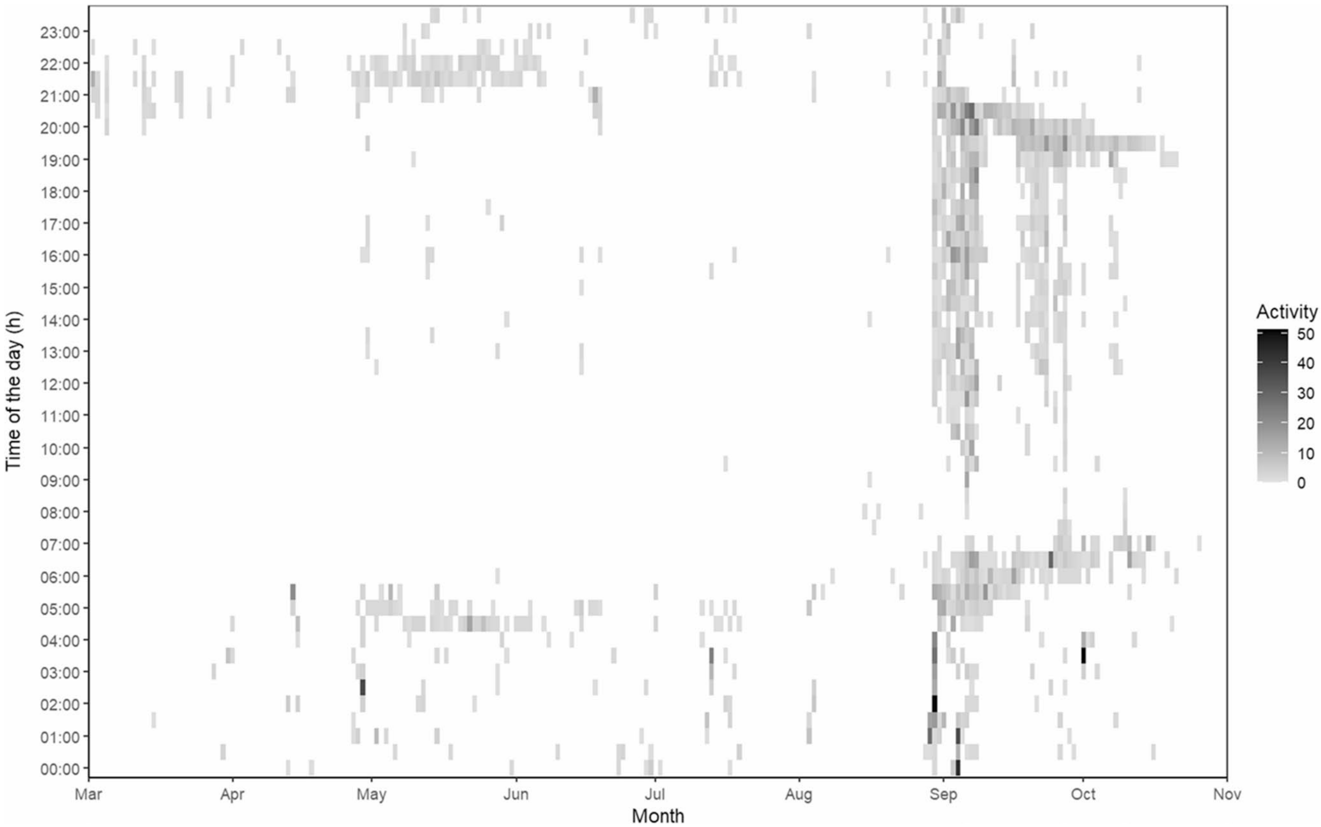

Fig. 6 Actogram showing the activity of the hazel dormice through the nest box entrance equipped with a TTP223 touch sensor as part of the Dormouse Data Logger Generation 3 (DDL3). Activity is defined as the number of sensor passages per 30 min with a 5 s blocking time between trigger events

measurement yielded 17 g, compared to the most recent automated DDL3 reading of 17.7 g, representing a 4% difference. The dormouse remained torpid during handling and was returned immediately to the nest box. On 11 April, a dormouse visited the logger and was weighed at 16.09 g. The tail length was not visible in the photo, making it uncertain whether this was Dormouse 1. No nest had been built during this period.

The first third of April 2024 was characterised by exceptionally warm conditions in and around Jena, with plant phenology such as flowering time advanced by approximately 14 days compared to the 30-year reference data (Deutscher Wetterdienst 2024). This early warming coincided with active use of the nest box as a daytime refuge by Dormouse 1, along with increased nocturnal activity of 20 sensor passages per 30-minute interval during the morning of 14 April. Beginning on 16 April, a cold air mass originating from northern Europe moved into Germany (Deutscher Wetterdienst 2024), leading to a pronounced drop in nest box temperatures: from 7.52 °C on 15 April to 4.45 °C on 19 April, reaching a minimum of −1.89 °C on 23 April. Temperatures began to increase thereafter, reaching 4.4 °C on 26 April and climbing to 11 °C by 28 April (Fig. 8a). During this period of low temperatures, one or both dormice entered torpor because of reduced activity that was evident between 15 April, 05:00, and 27 April, 03:00, with only two sensor passages recorded. In addition, the weight measurements on the load cell remained largely stable between intervals, further indicating a state of torpor (Fig. 7b). There was no evidence of nest box avoidance behaviour of hazel dormice during high temperatures. The nest box was heavily utilised during early September. At the same time, the highest internal temperatures of approximately 25–30 °C were measured.

From March to November, mean nest box temperature was 13.96 ± 6.50 °C (SE = 0.06), while relative humidity averaged 75.51 ± 11.71% RH (SE = 0.10). Nest box activity during this period averaged 0.30 ± 1.68 sensor passages per 30-minute interval (SE = 0.01). Activity peaked in September, with a mean of 1.63 ± 3.61 passages per 30-minute interval (SE = 0.10). A positive and statistically significant association was detected between nest box temperature and activity across the study period (Spearman's rank correlation: $Z = 24.20$, $p < 0.001$, $\rho = 0.19$).

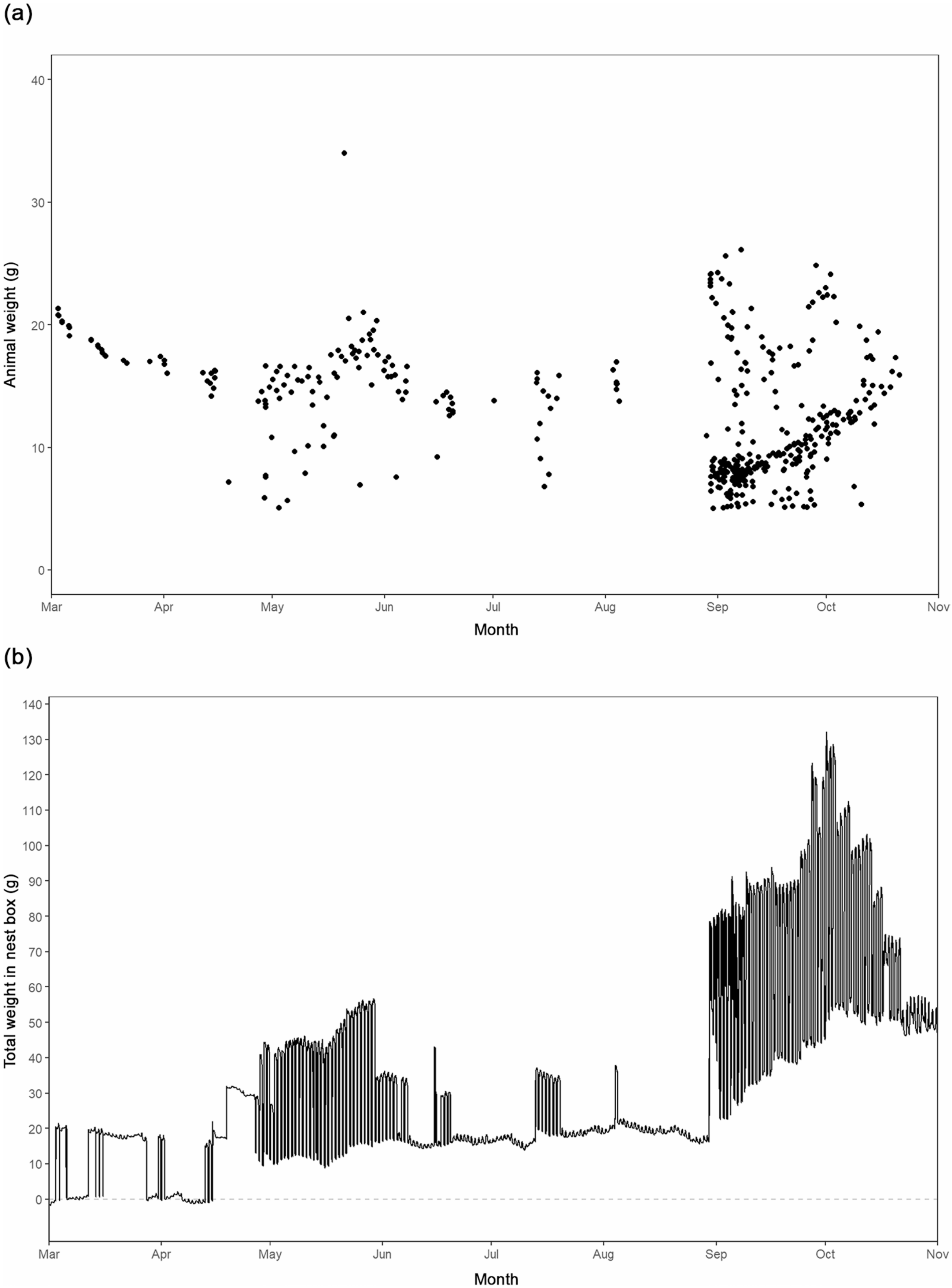
(a)
Animal weight (g)
0
10
20
30
40
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month
(b)
Total weight in nest box (g)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month

Fig. 7 **(a)** Animal weight recorded by the weighing routine of Dormouse Data Logger Generation 3 (DDL3); each data point was determined in a different 30-min interval **(b)** interval-based weighing data recorded continuously throughout the season

Monitoring of nest construction and second torpor event

On 13 April, a dormouse with a long tail was recorded at a weight of 15.42 g. Increased activity was observed on 14 April between 5:00 and 5:30, with 20 sensor passages recorded within 30 min (Fig. 6). Nest construction began on 14 April by an individual with a long tail, which added several leaves between 5:00 and 6:00 before resting, grooming, and exiting the box at 21:00 (Fig. 5c). The nest building was completed by Dormouse 1 on 15 April between 4:00 and 5:00, approximately 23 h after the first leaf was placed in the box. At this point, the weight of the nest material was approximately 10 g (Fig. 7b). One of the two dormice remained in the nest continuously from that point until 18 April. On 19 April at 00:00, the second dormouse entered the nest box, and both the dormice remained there together until 26 April (Fig. 7b).

Observation of activity following nest construction

Following nest construction, both dormice exhibited a regular pattern of activity from 27 March onwards. Typically, they entered the nest box together at dawn, used it as a daytime shelter, and departed together at dusk (Figs. 6 and 7b). During this period, their body mass gradually increased, reaching approximately 18–20 g by the end of May (Fig. 7a). After this time, the box was primarily used by a single dormouse until 7 June, with one joint occupation recorded on 15 June. From 7 June to 30 August, the box was visited only occasionally by one of the two individuals.

Monitoring nest box occupancy by mother and young

On 30 August, one dormouse brought additional nesting material, primarily fresh beech leaves, into the box, as documented by the camera system. Concurrently, the DDL3 recorded a body mass typical for adult hazel dormice of approximately 23 g, along with lower weights around 8 g, suggesting that a female dormouse and her offspring had relocated into the nest (Fig. 7a). By 2 September, three juvenile dormice were visible in camera footage, with recorded body masses of 6.43 g, 7.61 g, and 8.43 g. On 4 September, a female dormouse was photographed nursing her young inside the nest (Fig. 5f).

Between 30 August and 27 September, activity patterns changed noticeably compared to earlier periods, showing a marked increase in movement during daylight hours - except between 9 and 16 September during a time of colder temperatures (Figs. 6 and 8a). The peak activity occurred on 1 October at 03:30, with 51 sensor passages recorded within a 30-minute interval. The final instance of daytime activity was recorded on 10 October. Throughout the subsequent weeks, the dormouse family continued to utilise the nest box regularly, remaining inside during the day and vacating it during the night. By 21 October, the mean body mass of the juveniles had increased from approximately 7 g to 15 g (Fig. 7a), indicating a body mass gain of about 8 g over 50 days, equivalent to a growth rate of 0.16 g per day (2.29%).

Beginning on 3 October, the mother and young gradually vacated the nest box, as inferred from successive weight reductions (Fig. 7b). The first departure, likely that of the mother, corresponded to a recorded mass decrease of approximately 22 g. Subsequent decreases were recorded on 7 October (14 g), 13 October (16 g), 16 October (19 g), and 21 October (18 g), suggesting the sequential departure of the juveniles. On the final day of October 21, a dormouse with a 16 g body mass was recorded resting within the box from 06:00 to 19:00. The last activity detected at the entrance occurred on 2 November, although no weight change was recorded in the box and no corresponding weight measurement or photographic record was obtained.

Discussion

Monitoring of hazel dormouse activity and weight

Dormouse 1, distinguished by its short tail, entered the nest box unusually early in the season and stayed torpid for most of the time thereafter. According to Pretzlaff et al. (2021), hazel dormice in Germany typically hibernate from October to April. The animal was photographed and weighed during its first visit, and its weight and activity were subsequently monitored every half an hour. Such detailed observations would not have been possible through manual nest box checks, underscoring the potential of automated recording systems like the DDL3. The integrated camera, scale, and motion-sensing components facilitated the identification of torpor events.

Males typically awaken earlier in spring to secure territories (Juškaitis 2008). However, we were unable to confirm the sex of Dormouse 1 during the manual weight check, as it remained in a ball-like position due to being in torpor, and waking up the animal could have caused it to leave the nest box. A study in Lithuania found that individuals that show signs of tail autotomy are usually the exception in the dormouse population, with three-year-old males having the highest frequency of occurrence with 16.7% and

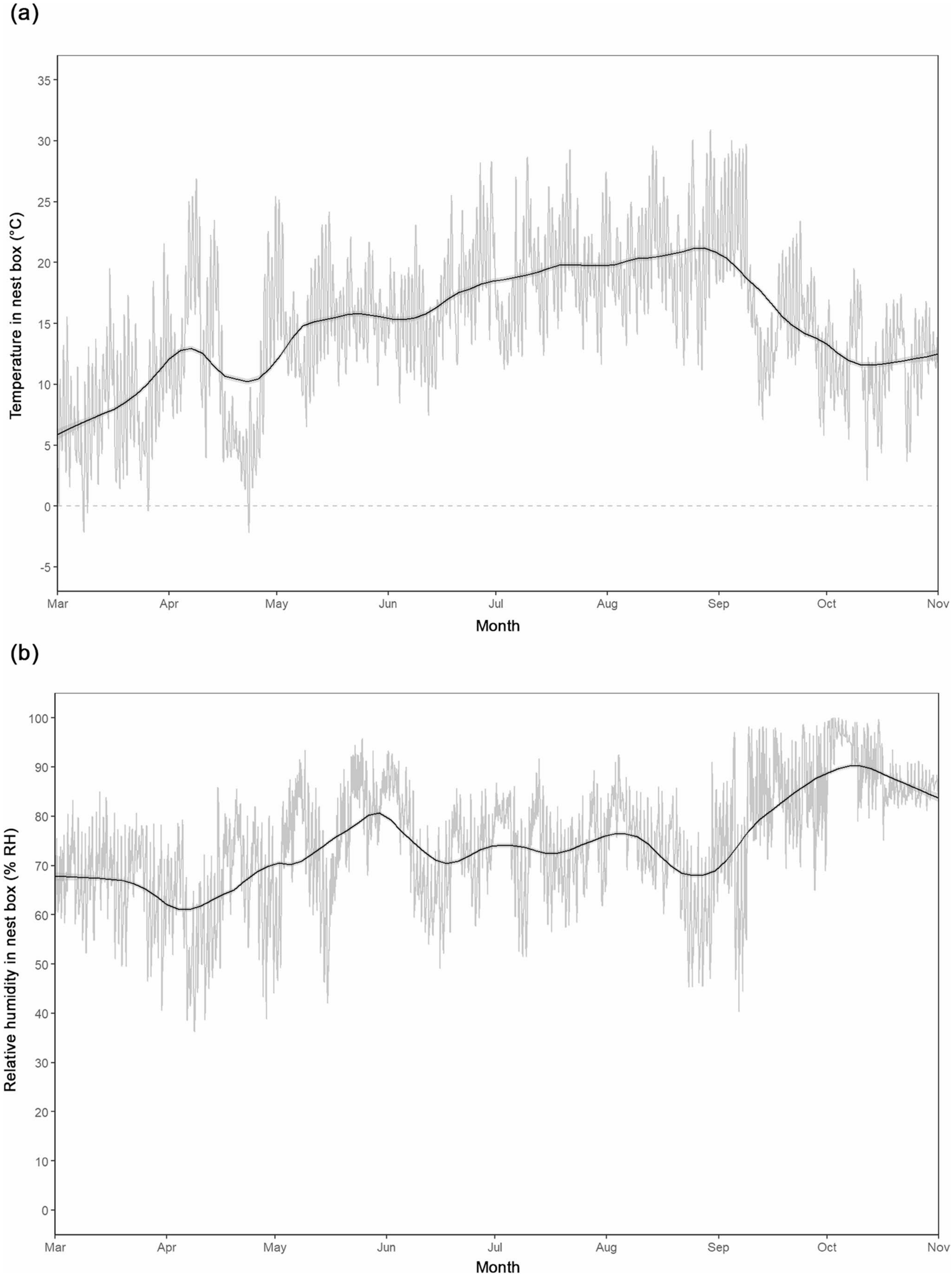
(a)
Temperature in nest box (°C)
35
30
25
20
15
10
5
0
-5
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month
(b)
Relative humidity in nest box (% RH)
100
90
80
70
60
50
40
30
20
10
0
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month

Fig. 8 **(a)** Temperature within the nest box chamber; the dashed line marks 0 °C **(b)** nest box relative humidity within the nest box chamber. For both, the black line represents smoothing; data was recorded with the SHT-31 sensor of the Dormouse Data Logger Generation 3 (DDL3). Smoothing was performed using Locally Estimated Scatterplot Smoothing (LOESS), span = 0.15, degree = 1

young-of-the-year dormice of both sexes with only 1.4% (Juškaitis 2006). Therefore, we made the assumption that the short-tailed dormouse is the same individual. Since no dormouse was marked during the study, we could not make a distinction between long-tailed individuals.

The system furthermore enabled the detection of seasonal fluctuations in the body mass of hazel dormice and, with the scale and camera, provided an indication of how many individuals were found within the nest box at the same time. Additionally, the camera captured behavioural data, documenting cooperative nest construction and offspring rearing by the mother.

The hazel dormouse young relocated in the nest box together with their mother at the end of August, suggesting they may have originated from another nest. Hazel dormice often use multiple nests and may relocate after significant disturbances (Moffatt 2017). Nest selection is furthermore influenced by food availability and protection from predators (Juškaitis et al. 2013).

In September, the female hazel dormouse and her young exhibited a shift from nocturnal to diurnal activity. Similarly, Walhovd (1971) observed this shift in a pair of confined hazel dormice during October. An explanation for this change in the circadian rhythm of hazel dormice can be that in autumn, energy-rich seeds and soft mast become available, providing an important food source for reaching the critical weight necessary for hibernation (Csorba 2003; Juškaitis 2007).

Monitoring of nest box temperature and humidity

Elevated ambient temperatures are considered a key trigger for dormouse arousal, with arousal events occurring more frequently during warmer periods (Pretzlaff and Dausmann 2012; Pretzlaff et al. 2021). Although Dormouse 1 appeared in the nest box in early March, it remained largely torpid while nest box temperatures stayed below 15 °C, a threshold commonly associated with torpid behaviour in dormice (Juškaitis 2005).

From September to October, humidity levels in the nest box rose, likely due to the occupancy of at least five hazel dormice and the concurrent decline in ambient temperatures. Maintaining higher and more stable humidity levels may be critical for hazel dormice, particularly during hibernation when evaporative water loss of an animal is critical (Findlay-Robinson and Hill 2024).

Limitation and optimisation of the data logger

The camera of the DDL3 proved to be a helpful tool in identifying species and even individuals when they show peculiarities like a shortened tail. However, during nest construction, accumulated nesting material can partially obstruct the camera's view, as seen to some extent in Fig. 5f, limiting its effectiveness until cleared during manual inspections. The animals showed no sign of disturbance from, nor interest in, the infrared LED or camera.

Although a weight check using a conventional spring scale did not show significant differences compared to the logger's recorded weight, the early emergence of the dormouse in the nest box meant that only a limited number of values for calibrating the scale with an empty weighing pan were recorded. This led to a lower fit in the linear regression and a slight fluctuation in the recorded weight due to temperature changes, seen as small daily-based deviations in Fig. 7b. Additionally, minor weight oscillations could be attributed to the moisture absorption of the hygroscopic nesting material, as shown by the camera footage capturing its daily expansion and contraction inside the nest box.

Enhancements to improve the functionality of the DDL3 can include optimising the weighing routine and adjusting the design of the weighing pan. A distinction between a dormouse and a dormouse carrying nesting material or young has not been made by the dormouse weighing routine and can only be achieved manually by retrospectively connecting the animal weight and nest box total weight with the corresponding photo taken. The outlier in animal weight recorded on May 20th, at 34.01 g, was likely caused by two animals entering the box immediately after one another and resting on the weighing pan together. Increasing the height of the weighing pan's walls would prevent the nest from coming into contact with the wooden box, thereby enhancing the accuracy of weight measurements. Due to the walls of the weighing pan, the extraction of the nest or animal for manual weighing in the DDL3 is, however, more difficult than in a conventional dormouse nest box. For improvement, removable side walls or access from the top should be considered.

Because the animals were not individually marked, e.g., with internal or external Passive Integrated Transponder (PIT) tags, and the logger lacks an RFID reader, distinguishing between individuals of similar weight is challenging. Incorporating an RFID reader and marking animals with PIT tags could greatly enhance the ability to assign data to specific individuals for different research questions.

Implication for conservation

Due to its modular, 3D-printable design, the DDL3 can be easily adapted for a wide range of research applications involving nest studies of dormice. Minor modifications to the nest box structure can make it suitable for monitoring other cavity-nesting species that readily use artificial nest boxes, broadening its applicability across species and taxa. This flexibility enables simultaneous monitoring of environmental conditions, in-nest microclimate, body mass, and behavioural patterns, including circadian activity, nesting behaviour, and social interactions - facilitating the investigation of diverse ecological questions. The DDL3 can be integrated into conventional field studies and used alongside other automated systems, such as the Dormouse Monitoring System (DoMoS, Büchner et al. 2022), an automated sampling device for garden dormice, to gain deeper insights into dormouse ecology.

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Author contributions CS: Designing the study; formulating methodology; developing the data logger; conducting fieldwork; data analysis and interpretation; conceptualising and writing the manuscript. AC: Data analysis and interpretation; conceptualising and writing the manuscript.

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Data availability Data is provided as supplementary files: B7 Season 2024 Data.xlsx; B7 Season 2024 Photos.zip; B7 Season 2024 Time Lapse Video.mp4.

Declarations

Ethics declaration All research in the field has been carried out under nature conservation law permit granted to Clemens Schulze by the city of Jena - Fachdienst Umweltschutz from 21 February 2022. (Reference UNB-AS-BE-AG-2022-05)

Competing interests The authors declare no competing interests.

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