

Article

Wintering Conditions and Heat Loss during Hibernation in the Brown Long-Eared Bat

Grzegorz Klys ^{1,*}  and Joanna Makuchowska-Fryc ² 

¹ Institute of Biology, University of Opole, ul. Oleska 22, 45-052 Opole, Poland

² Institute of Environmental Engineering and Biotechnology, University of Opole, ul. Kardynała B. Kominka 6, 45-032 Opole, Poland; amak@uni.opole.pl

* Correspondence: gklys@uni.opole.pl

Abstract: The aim of this study was to estimate heat loss in the brown long-eared bat during hibernation depending on the refugiolclimate conditions. The measured values of refugiolclimate parameters were: ambient temperature (T_a) 3–10 °C, relative humidity (Rh) 74–98% and air velocity (v) 0.06–0.95 m/s. Heat loss was calculated using convective heat transfer equations. Mean heat loss amounted to 4 W/m². The results were compared to the heat loss calculated based on the fat burned during hibernation. Bats flying into underground systems during the hibernation period were captured and their body mass was measured. A loss of body mass of 2.6 g over the 126 days of hibernation was observed. Heat loss equalled 3.115 W/m²K. The presented method of calculating energy expenditure allows for non-invasive monitoring of the heat and fat losses of bats during hibernation. Such research may find application in designing artificial wintering sites.

Keywords: chiroptera; *Plecotus auritus*; thermoregulation; microclimate selection; hibernation monitoring

1. Introduction

The microclimate of a refuge (the refugiolclimate) affects the survival of bats during winter [1–3]. Each species has its own preferences regarding the refugiolclimate [4–6]. In addition, the makeup of a refugiolclimate determines both the thermal comfort and frequency of awakenings [2,7–9].

The interior microclimates of underground environments (caves, adits, bunkers, etc.) where bats hibernate can be highly diverse due to the number of entrances, airflow direction and velocity, depth and other properties of each underground system [10,11]. The field of science that researches and analyses such microclimates is called *micrometeorology* [12–15], sometimes referred to as *cave meteorology* [16].

Hibernation occurs as a response to unfavourable environmental conditions. In order to survive this period, the hibernators must accumulate fat and find a suitable site, where they can lower their body temperature and maintain it at an appropriate level, usually close to that of the ambient temperature.

Metabolism slows down considerably during hibernation. Many researchers address the problem of changes in the metabolic rate and the effect of hibernation on the condition of the body [17–20].

The emission of heat from a bat's body into the surroundings takes place through convection, conduction, radiation and evaporation [21]. A few studies have attempted to measure the total energy expenditure during hibernation [18,22–27]. Furthermore, studies concerning energy expenditure to date have been based on incomplete conditions in the hibernaculum. The authors have usually only provided selected parameters of the underground microclimate, rather than the parameters of the refugiolclimate (primarily the ambient temperature, T_a) [28]. The modelling of energy transformation is based on the optimal values of the selected parameters, primarily T_a , or T_a and relative humidity (Rh) [2].



Citation: Klys, G.; Makuchowska-Fryc, J. Wintering Conditions and Heat Loss during Hibernation in the Brown Long-Eared Bat. *Appl. Sci.* **2024**, *14*, 716. <https://doi.org/10.3390/app14020716>

Received: 4 November 2023

Revised: 16 December 2023

Accepted: 11 January 2024

Published: 15 January 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

This leads to discrepancies between the calculated and the observed hibernation time. In contrast, there are many studies concerning the effect of T_a , R_h and airflow velocity (v) on human thermal comfort and human energy expenditure, for instance, in mines [29,30].

The aim of this study was to estimate heat loss in the brown long-eared bat *Plecotus auritus* (Linnaeus, 1758) during hibernation depending on the refugiolclimate conditions, as determined by T_a , R_h and v . Heat loss was calculated using convective heat transfer equations. The results were compared to the heat loss calculated based on the fat burned during hibernation.

2. Methods

This study was conducted in underground systems located in the *Międzyrzecki Rejon Umocniony* ('Strengthened Area of Międzyrzecki', MRU) [31] and in the *Podziemia Tarnogórsko-Bytomskie* ('Tarnogóra and Bytom Underground', PTB) [32] in Poland. Data related to the refugiolclimate were collected with permission from the Voivodeship Nature Conservators and the Minister of Environment (DOPog-4201-04A-2/03/al.; DOPog-4201-04A-6/04/al.; DLOPiK-op/Ozgi-4200/IV.D-16/6568/06/aj). The principal criterion for the selection of the research sites was a large population of wintering *Plecotus auritus* specimens.

2.1. Body Mass Measurement

In order to measure the loss of body mass over the winter, bats were captured between 11 October 2003 and 8 May 2004 at approximately two-week intervals. Bats flying into the PTB underground system were captured using D 70/16 chiropterological mist-nets. Body mass was measured using a Pesola Light Line 20 g/02 dynamometer, modernised and calibrated for the purposes of this study, with a range of 0–20 g and an accuracy of ± 0.1 g.

2.2. Refugiolclimate Parameter Measurement

Data concerning the refugiolclimate (T_a , R_h , absolute air pressure p , and v) were collected independently during the peak of hibernation (December–February) in 2002 and 2007 in the MRU. The hibernating animals were not woken up, and their gender and age were not determined. The SENSOTRONMPG22 measurement devices, modified and calibrated for the purposes of this study, were used with the following accuracy ratings:

- Gas parameter metre—for humidity (R_h), range of 0–100%, resolution of indications 0.1% with an uncertainty of indications $\pm 1.5\%$; for temperature (T_a), range of $-50 \div 200$ °C, resolution of indications 0.1 °C with an uncertainty of ± 0.1 °C; and for atmospheric pressure (p), range of 500–1500 hPa, resolution of indications 1 hPa with an uncertainty of ± 2 hPa;
- Thermo-anemometer (portable digital air speed (v) and temperature metre)—the measurement range was 0.01–20 m/s, with an uncertainty of indications ± 0.01 m/s.

The measurements were taken from the side of the incoming air using an extendable arm to prevent the observer from interfering with the readings. The values of atmospheric pressure were transformed into values of p for 1000 hPa using the 'Mollier-x Chart' program in order to facilitate a comparison between the R_h readings obtained from different measurement locations and days with significant differences in pressure.

2.3. Heat Loss Calculation

(a) Based on fat burned

The energy reserve (ER) was estimated using the cost of hibernation of an average specimen, based on measurements of the body mass of *Plecotus auritus* specimens flying into the PTB.

$$ER = m_{fat} \cdot q_{fat\ burn} \quad (1)$$

where the variables represent the following:

ER —energy reserve, J.

m_{fat} —mass of fat, g.

$q_{fat\ burn}$ —energy according to Poczopko [33] 39.75 kJ/g.

The amount of heat generated by burning the accumulated fat throughout the period of hibernation was calculated using the following formula:

$$Q_{hib} = \frac{ER}{\tau} \quad (2)$$

where the variables represent the following:

Q_{hib} —heat, W.

τ —hibernation time, s.

Heat loss was calculated per 1 m² of the body surface area of the bat, based on the average size of a specimen of this species [34], i.e., height of 0.04 m, width of 0.026 m and thickness of 0.013 m.

$$q_{hib} = \frac{Q_{hib}}{S} \quad (3)$$

where the variables represent the following:

q_{hib} —density of heat flux, W/m².

S —surface, m².

The mean surface of a specimen was calculated by simplifying the shape of the bat into that of a cylinder:

$$S = 2\pi r(r + h) = 3.048 \times 10^{-3} \text{ m}^2 \quad (4)$$

where the variables represent the following:

h —height (0.04 m).

r —radius of the cylinder, calculated as the average of thickness and width (9.75×10^{-3} m).

The heat loss values calculated from the fat burned were compared to those calculated with the inclusion of the heat exchange between the bat's body and the surroundings.

(b) Based on refugiolclimate parameters

The measurements of the refugiolclimate parameters and body temperature (T_b) were used for the calculations. To simplify the calculations, the following assumptions were made: the surface of the bat adjoining the terrain was minimal and limited to the bat's points of attachment and fulcrums; the air flowed over the bat's entire body; and the heat exchange was described by Newton's law:

$$q_{hib} = \alpha \cdot \Delta t \quad (5)$$

where the variables represent the following:

α —heat transfer coefficient, W/m²K.

Δt —difference between the bat's body temperature, T_b , and the ambient temperature, T_a (K).

During hibernation, the difference between T_b and T_a in *Plecotus auritus* amounts to approximately 1 degree ($\Delta t \approx 1$) [6,35–37]; therefore,

$$\alpha = q_{hib} \quad (6)$$

The heat transfer coefficient (α) was calculated based on equations for forced convection. The air flux was assumed to be perpendicular to the bat's body, which for the purposes of the calculations was treated as a cylinder. Consequently, the Zukauskas equation for air was applied [38]:

$$Nu = 0.216 \cdot Re^{0.6} \quad (7)$$

where the variables represent the following:

Re —Reynolds number.

Nu —Nusselt number.

The Reynolds number was calculated using the following formula:

$$Re = \frac{w \cdot l}{\nu} \quad (8)$$

where the variables represent the following:

w —air velocity, m/s.

l —characteristic dimensions (diameter of the cylinder), m.

ν —kinematic viscosity coefficient of the air, m²/s.

$$Nu = \frac{\alpha \cdot l}{\lambda} \quad (9)$$

where the variables represent the following:

λ —thermal conductivity coefficient of the air, W/m·K.

α —heat transfer coefficient, W/m²·K.

Thus, α was given by

$$\alpha = \frac{Nu \cdot \lambda}{l} \quad (10)$$

3. Results

3.1. Body Mass Measurement

Table 1 shows the results of measurements of the body mass of all bats flying into and out of the PTB.

Table 1. Variation in mean body mass of the *Plecotus auritus* specimens over time.

Data	m	sd	Cv	n	N
11 October 2003	8.2	1.34	16	91	0
25 October 2003	9.8	1.31	13	38	14
8 November 2003	9.9	0.86	9	38	14
22 November 2003	9.7	1.07	11	15	14
13 December 2003	8.3	0.94	11	10	21
27 December 2003	9.3	1.24	13	7	14
4 January 2004	8.3	0.82	10	5	8
24 January 2004	8.6	1.56	18	8	20
7 February 2004	7.6	0.93	12	14	14
21 February 2004	7.6	0.57	8	16	14
13 March 2004	7.3	1.22	17	25	21
27 March 2004	8.8	0.95	11	37	14
10 April 2004	7.9	0.80	10	44	14
24 April 2004	7.7	0.75	10	22	14
8 May 2004	9.3	0.58	6	3	14

where m—mean body mass [g], sd—mean standard deviation [g], Cv—coefficient of variation [%], n—number of measurements, N—number of days between measurements.

The data shown in Table 1 were used to distinguish the periods of increases and decreases in the mean body mass of the bats. The loss of body mass during hibernation is shown in Figure 1.

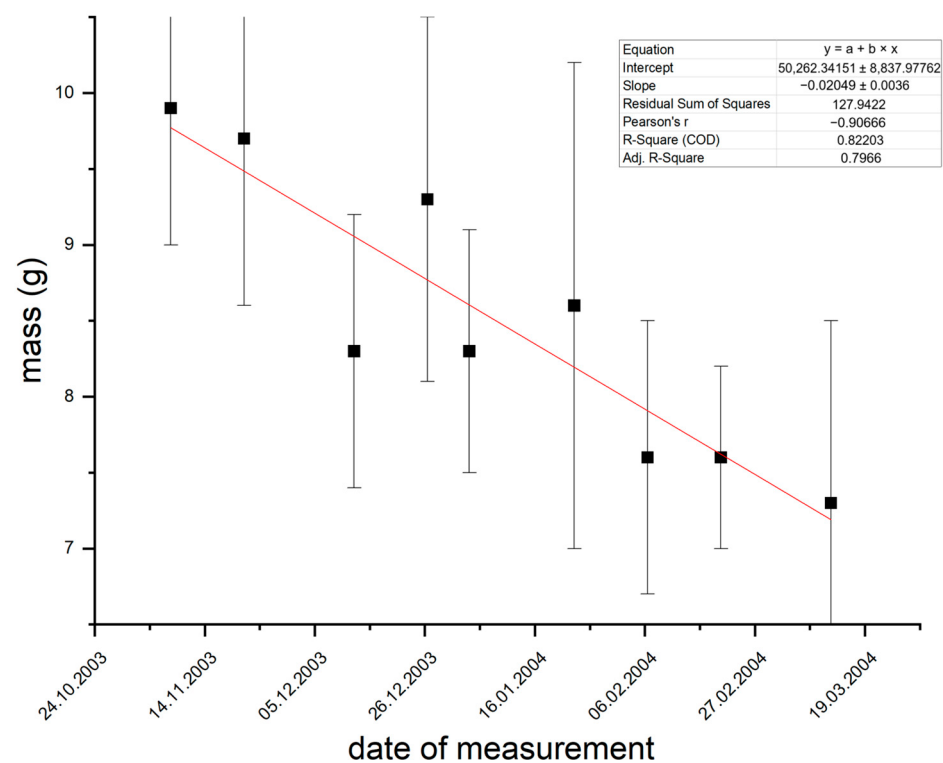


Figure 1. Changes in the body mass of *Plecotus auritus* during hibernation. The whiskers denote the standard deviation of a series of measurements.

The maximal body mass of the bats (9.9 g) was registered on 8 November 2003. The minimal body mass was registered on 13 March 2004. The mean loss of mass based on the trend line (Figure 1) equalled 2.6 g and took place over 126 days, which constituted about 26% of the bats' body mass compared to the mass prior to hibernation. The variation in the body mass measurements was low ($C_v < 25\%$).

3.2. Refugiolclimate Parameter Measurement

Table 2 presents the mean values of the parameters of the refugiolclimate obtained in the MRU in 2002 and 2007.

Table 2. Values of the parameters of the refugiolclimate in the MRU.

Date	T, °C	sd T, °C	Cv, %	Rh, %	sd H _r , %	Cv, %	v, m/s	sd v, m/s	Cv, %	P, hPa	n, -
4 January 2002	3.0	0.96	30	98.0	0.57	1	0.08	0.01	11	1000	30
19 January 2002	3.0	1.23	47	97.0	0.89	1	0.07	0.02	28	1000	30
1 February 2002	5.0	1.15	22	97.0	0.65	1	0.06	0.02	26	1000	34
22 February 2002	5.0	1.35	27	97.0	0.84	1	0.06	0.01	19	1000	28
8 December 2002	5.0	1.53	31	97.0	0.64	1	0.07	0.01	17	1000	28
21 December 2002	6.0	1.26	23	97.0	0.50	1	0.07	0.01	13	1000	26
5 January 2007	8.0	0.41	5	82.0	2.87	4	0.36	0.13	38	1000	58
6 January 2007	10.0	0.55	6	74.0	25.64	35	0.21	0.01	47	1000	55
7 January 2007	9.0	0.60	7	81.0	1.93	2	0.06	0.04	60	1000	3
8 January 2007	9.0	0.22	3	82.0	1.76	2	0.06	0.04	59	1000	24

Table 2. Cont.

Date	T, °C	sd T, °C	Cv, %	Rh, %	sd H _r , %	Cv, %	v, m/s	sd v, m/s	Cv, %	P, hPa	n, -
9 January 2007	10.0	0.39	4	91.0	0.63	1	0.50	0.29	58	1000	5
7 February 2007	7.0	0.77	12	89.0	3.36	4	0.95	0.35	36	1000	25
8 February 2007	8.0	0	0	84.0	0	0	0.61	0.04	7	1000	4
9 February 2007	7.0	0.45	6	85.0	10.32	12	0.54	0.03	6	1000	8
11 February 2007	10.0	1.15	11	-	-	-	0.53	0.53	100	1000	8
13 February 2007	7.0	1.35	18	84.0	6.03	7	0.22	0.19	83	1000	74
14 February 2007	9.0	0.41	4	88.0	0.37	0	0.20	0.04	18	1000	6
15 February 2007	9.0	1.13	12	78.0	5.94	8	0.08	0.05	66	1000	86

—no measurement, n—number of specimens.

3.3. Heat Loss Calculation

(a) Based on fat burned

Next, the ER of an average *Plecotusauritus* specimen was calculated following the assumption that the mean loss of mass was directly related to the burning of 2.6 g of fat in order to cover the expenditure during hibernation.

$$ER = 2.6 \cdot 39.75 = 103,350 \text{ J}$$

The heat generated by a specimen during hibernation (Equation (2)) amounted to

$$Q_{hib} = \frac{103,350 \text{ J}}{126 \text{ days} \cdot 24 \text{ h} \cdot 3600 \text{ s}} = 9.493 \text{ E} - 3, \text{ W}$$

The heat loss relative to 1 m² of the surface area of a specimen's body (Equation (3)) equalled

$$q_{hib} = \frac{9.493 \text{ E} - 3 \text{ W}}{3.048 \text{ E} - 3 \text{ m}^2} = 3.115 \frac{\text{W}}{\text{m}^2}$$

(b) Based on refugioclimate parameters

Table 3 presents the heat loss calculated based on the parameters of the refugioclimate (Equations (5)–(10)). The values represent the mean value (q_{hib}) for each day of measurement.

Table 3. Heat (q_{hib}) lost from the surface of a specimen's body into the surroundings in the MRU.

Measurement Date	q_{hib} , W/m ²	sd q_{hib} , W/m ²	Cv, %	n, -
4 January 2002	2	0.2	7	30
19 January 2002	2	0.4	18	30
1 February 2002	2	0.3	15	34
22 February 2002	2	0.2	11	28
8 December 2002	2	0.2	11	28
21 December 2002	2	0.2	8	26
5 January 2007	5	1.6	28	58
6 January 2007	4	1.2	31	55
7 January 2007	2	0.7	37	3
8 January 2007	2	0.7	36	24

Table 3. Cont.

Measurement Date	q_{hib} , W/m ²	sdq_{hib} , W/m ²	Cv, %	n, -
9 January 2007	6	3.3	51	5
7 February 2007	10	2.5	26	25
8 February 2007	8	0.3	4	4
9 February 2007	7	0.3	4	8
11 February 2007	6	4.1	65	8
13 February 2007	4	2.1	54	74
14 February 2007	4	0.4	12	6
15 February 2007	2	1.1	54	86

The mean values of q_{hib} on each day of measurement showed a normal distribution. The mean heat loss during hibernation (q_{mean}), calculated as the arithmetic mean of the results provided in Table 3, amounted to 4 W/m².

4. Discussion

The main question asked in every study on the energetics of hibernation is whether the fat reserves of a specimen are sufficient to survive the period of hibernation [26].

The content of fat in the bodies of some species of bats prior to their entry into hibernation ranges from 1/5 to 1/3 of the dry weight of their bodies [33]. Studies on hibernation have rarely addressed the topic of estimating the total energy expenditure and fat use in hibernating bats [22–25]. Koteja [24] analysed the energy balance in the greater mouse-eared bat (*Myotis myotis*) during hibernation. They concluded that from a mean weight of about 29 g in the autumn, the species burns about 4.9 g of fat over the course of hibernation (165 days). Thomas [27] estimated that the little brown bat (*Myotis lucifugus*) uses about 2 g of its 6.5 g weight over the course of hibernation (193 days). In addition, Harje [39] demonstrated that the Daubenton's bat (*Myotis daubentoni*) loses 30–40% of its autumn body mass (37% on average) over the course of 200 days. The big brown bat (*Eptesicus fuscus*) burns 3 g of fat out of its autumn weight of 20 g [40].

In most studies, it is assumed that the content of fat in a bat's body prior to hibernation ranges from 25% to 30% of the total body weight [5]. The energy balance during hibernation is usually modelled based on a constant weight loss of 30% [9,41]. Cheng [42] proposed changing this approach after demonstrating that specimens with less fat content in their bodies burn fat at a reduced rate.

Koteja [24] stated that the rate at which a bat burns fat differs considerably depending on the site and the phase of hibernation, although the total fat loss for a given species remains the same across different underground systems. Ransome [25] also observed major differences in the rate of fat burning in his study on the greater horseshoe bat (*Rhinolophus ferrumequinum*).

The loss of body mass measured in the PTB amounted to 2.6 g, with a pre-hibernation mass of 9.9 g, which constituted about 26% of a bat's average mass. According to Hranac [2], the lean body mass of bats usually remains constant, which means that any loss of mass can be attributed to fat being burned.

The mean heat loss estimated based on the amount of fat burned amounted to 3.115 W/m². However, this study did not take into account differences in sex, age, physical condition, size or hibernation strategy. Furthermore, the estimated heat loss may have been burdened with an error resulting from the method used to calculate the hibernation time. Usually, the hibernation time in bats is determined based on the number of nights with a mean recorded temperature of below 0 °C [9,41]. However, some populations of bats may awaken from hibernation even when the ambient temperature drops below 0 °C. Bats wake up from hibernation repeatedly, but do not leave their wintering grounds. According to the

subject literature, over 60% of bat awakenings are cold awakenings, which use up less fat while allowing the bats to change their hibernation site [43]. However, some specimens fly into and out of the underground systems throughout the entire period of hibernation. The authors of this study used such specimens to measure their body mass in order to avoid waking up the hibernating bats. This suggests the existence of more complex determinants of the awakening time [44]. Hranac [2] proposed improving the accuracy of determining the hibernation time by also taking into account the height and latitude, in addition to the number of days with below-freezing temperatures. Hibernation takes place in a period when, in addition to unfavourable temperatures, the bats experience a shortage of food. Consequently, the bats are forced to use their accumulated fat reserves. The authors of this study defined hibernation time as the time from the day when the bats' maximal body mass was observed (in bats flying into the cave) to the day when the minimal body mass was observed. According to the authors' investigations, hibernation time defined in this manner is consistent with the field observations of various species of bats (different species have different hibernation times, despite wintering in the same climate).

The metabolic rate in hibernating bats decreases with body temperature [18,45]. However, temperature is not the only factor that affects the amount of heat generated in a bat's body. Bats may be able to control their energy expenditure regardless of the ambient temperature and drastically decrease it when at risk of depleting their fat reserves [24]. According to Hranac [2], the primary parameters that determine the rate of metabolism are temperature and relative humidity. Their modelling was based on an optimal temperature (4 °C) and a relative humidity (98%) that can ensure the longest possible hibernation time in *Myotis lucifugus*. Furthermore, Klüg-Baerwald [46] emphasised the importance of the interaction between temperature and air velocity for the bats' winter activity.

The actual wintering conditions differ, both between different bat species and within a given species inhabiting the same cave [6]. *Plecotus auritus* prefers underground systems with a temperature ranging from 0.0 to 9.0 °C for hibernation [4,47–52]. However, these values were provided without specifying whether they concerned the underground microclimate or the refugioclimate. In this study, the following ranges of refugioclimate parameters were observed in the MRU: T_a 0.7 ÷ 11.5 °C, Rh 56.7 ÷ 100% and v 0.01 ÷ 1.43 m/s.

In general, healthy bats are assumed to be able to reduce fat loss during winter by choosing a microclimate that allows for fewer awakenings [1,22,53–55]. An appropriate microclimate may ensure the longest possible hibernation time [8]. Many publications confirm that multiple independent factors may affect energy expenditure in hibernating mammals [56–58]. However, T_a is usually considered the most important of these factors. McGuire [59] demonstrated that T_a , humidity and the condition of the body contribute to energy expenditure during hibernation.

The authors of this study believe that the key factors are air temperature (T_a), airflow velocity (v) and relative humidity (Rh). Ambient temperature and airflow velocity determine the intensity of the heat exchange between the body of a hibernating bat and its surroundings by means of convection. This is reflected in the formulas for convection (airflow velocity affects the type of flow: turbulent, transitional or laminar). Furthermore, the metabolic rate increases at high ambient temperatures, which causes faster burning of the fat reserves. Consequently, high airflow velocities allow the bats to lower their body temperature. Conversely, humidity affects the intensity of the exchange of mass between the body and the surroundings (leading to the loss of water by the bats).

In 2002, the refugioclimate was observed to have stable parameters, with low values of T_a (3–6 °C) and v (0.06–0.08 m/s) and high values of Rh (97–98%), while in 2007, high values of T_a (7–10 °C) and v (0.06–0.95 m/s) were noted, with much lower values of Rh (74–91%).

The authors observed that *Plecotus auritus* prefers humid refuges. A humid environment decreases the loss of water through evaporation and reduced energy expenditure [59,60]. A previous study (Table 2) showed that when the relative humidity was high

(over 97%), *Plecotusauritus* specimens chose sites with a slow (0.06–0.08 m/s) airflow and low temperature (3–6 °C).

In these conditions, the mean heat loss amounted to about 2 W/m² (Table 3). At a higher temperature (9–10 °C) and low Rh (ca. 74%), the bats selected sites with a high v (ca. 0.21 m/s), resulting in a mean heat loss of about 4 W/m². The highest heat loss (over 10 W/m²) occurred with a v of over 0.5 m/s. In these conditions, the T_a in the hibernaculum was 7–8 °C and the Rh was 80–90%.

The estimation of heat loss did not take into account the changes in a bat's body surface involved in the heat exchange. Speakman [61] observed a relationship between a bat's body temperature and the degree to which its ears stand out from the head and the regulation of the body surface in a temperature lower than the ambient temperature. Preliminary observations indicate that the surface area of a brown long-eared bat's body in contact with the surroundings changes significantly over the course of hibernation (Figure 2).



Figure 2. Changes in the body surface area of the brown long-eared bat during hibernation.

The estimation of heat loss in the bats based on heat exchange mechanics, which was performed using both the fat-burned method and the refugiolclimate parameters method, did not take into account the awakenings, which, despite constituting only a small fraction of the hibernation time, corresponded to a considerable portion of the expended energy. Thomas [27] reported that a single awakening uses up about 5% of a bat's total energy expenditure during hibernation. According to Klüg-Baerwald [46], bats do not wake up from torpor in order to refill their fat reserves; rather, they do so in order to find a site with a more beneficial refugiolclimate or to excrete metabolic products.

5. Summary

Over the 126-day-long hibernation of *Plecotusauritus*, its specimens lost 2.6 g of body mass. Heat loss calculated based on the fat burned over this period amounted to 3.115 W/m². Heat loss calculated based on the parameters of the refugiolclimate (T_a , Rh and v) and the bats' body temperature (T_b) equalled 4 W/m² and provided information about momentary heat loss (for a given refugiolclimate on different measurement days). They provide insight into the variation in the rate of fat consumption during hibernation. Averaging the results indicates the heat loss sustained by a given species during hibernation. Calculating the bats' energy expenditure by measuring the refugiolclimate parameters allows researchers to monitor the hibernation of bats over any length of exposure and frequency of readings with minimal intervention (since the parameters of the surroundings, rather than the bats themselves, are measured) and to determine the potential hibernation time. In addition, it allows for the identification of potential hibernation sites where parameter values are favourable in terms of the use of fat reserves. Such research may find application in designing artificial wintering sites.

Author Contributions: Conceptualization, G.K. and J.M.-F.; Formal analysis, J.M.-F.; Resources, G.K.; Data curation, J.M.-F.; Writing—original draft, G.K.; Writing—review & editing, G.K. and J.M.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financed by the University of Opole within the institutes: Biology, Environmental Engineering and Biotechnology.

Institutional Review Board Statement: Research on collecting bat measurements and refugiolclimate measurements was collected with the consent of the Provincial Nature Conservators and the Minister of the Environment (DO-Pog-4201-04A-2/03/al.; DOPog-4201-04A-6/04/al.; DLOPiK- op/Ozgi-4200/IV.D-16/6568/06/aj). The ethical review and approval of this study was waived due to the fact that the study only involved temporarily keeping the animal in order to collect morphometric data. At the same time, there are no alternative solutions to the above-mentioned implementation, research and photographic documentation without performing the activities referred to in Art. 52 section 1 points 2, 12 and 14 of the Nature Protection Act. Moreover, these activities are necessary to carry out scientific research and will be used to supplement knowledge about the species composition of chiroptero fauna in the region. Therefore, the decision in question meets all the criteria for issuing a permit to perform prohibited activities in relation to protected species referred to in Art. 56 section 4 of the Nature Protection Act. When issuing this decision, the principle set out in Art. 7 of the Act of 14 June 1960, Code of Administrative Procedure, was cited.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Boyles, J.G.; Dunbar, M.B.; Storm, J.J.; Brack, V., Jr. Energy availability influences microclimate selection of hibernating bats. *J. Exp. Biol.* **2007**, *210*, 4345–4350. [\[CrossRef\]](#)
- Hranac, C.R.; Haase, C.G.; Fuller, N.W.; McClure, M.L.; Marshall, J.C.; Lausen, C.L.; McGuire, L.P.; Olson, S.H.; David, T.S. What is winter? Modeling spatial variation in bat host traits and hibernation and their implications for overwintering energetics. *Ecol. Evol.* **2021**, *11*, 11604–11614. [\[CrossRef\]](#)
- Marroquin, C.M.; Lavine, J.O.; Windstam, S.T. Effect of Humidity on Development of *Pseudogymnoascus destructans*, the Causal Agent of Bat White-Nose Syndrome. *Northeast. Nat.* **2017**, *24*, 54–64. [\[CrossRef\]](#)
- Gaisler, J. Remarks on the thermopreferendum of Palearctic bats in their natural habits. *Bijdr. Dierk.* **1970**, *40*, 33–35. [\[CrossRef\]](#)
- Haase, C.G.; Fuller, N.W.; Dzal, Y.A.; Hranac, C.R.; Hayman, D.T.S.; Lausen, C.L.; Silas, K.A.; Olson, S.H.; Plowright, R.K. Body mass and hibernation microclimate may predict bat susceptibility to white-nose syndrome. *Ecol. Evol.* **2021**, *11*, 506–515. [\[CrossRef\]](#)
- Klys, G. *Multifactor Analysis of Refugiolclimate in Places of Hibernation of Chosen Bat Species*; Studia Chiropterologica: Annals of the Chiropterological Information Center: Krakó, Poland, 2013; Volume 8.
- Czenze, Z.J.; Park, A.D.; Willis, C.K.R. Staying cold through dinner: Cold-climate bats rewarm with conspecifics but not sunset during hibernation. *J. Comp. Physiol. B* **2013**, *183*, 859–866. [\[CrossRef\]](#)
- Haase, C.G.; Fuller, N.W.; Hranac, C.R.; Hayman, D.T.S.; Olson, S.H.; Plowright, R.K.; McGuire, L.P. Bats are not squirrels: Revisiting the cost of cooling in hibernating mammals. *J. Therm. Biol.* **2019**, *81*, 185–193. [\[CrossRef\]](#)
- Humphries, M.M.; Thomas, D.W.; Speakman, J.R. Climate-mediated energetic constraints on the distribution of hibernating mammals. *Nature* **2002**, *418*, 313–316. [\[CrossRef\]](#)
- McClure, M.L.; Haase, C.G.; Hranac, C.R.; Hayman, D.T.S.; Dickson, B.G.; McGuire, L.P.; Crowley, D.; Fuller, N.W.; Lausen, C.L.; Plowright, R.K.; et al. A hybrid correlative-mechanistic approach for modeling winter distributions of North American bat species. *J. Biogeogr.* **2021**, *48*, 2429–2444. [\[CrossRef\]](#)
- Perry, R.W. A review of factors affecting cave climates for hibernating bats intemperate North America. *Environ. Rev.* **2013**, *21*, 28–39. [\[CrossRef\]](#)
- Niedźwiedź, T. *Słownik Meteorologiczny*; Polskie Towarzystwo Geograficzne: Warszawa, Poland, 2003.
- Paszyński, J.; Miara, K.; Skoczek, J. Wymiana energii między atmosferą a podłożem jako podstawa kartowania topoklimatycznego. In *Dokumentacja Geograficzna 14*; Instytut Geografii i Przestrzennego Zagospodarowania PAN: Warszawa, Poland, 1999.
- Pawiński, J.; Roszkowski, J.; Strzeński, J. *Przewietrzanie Kopalń*; Śląskie Wydawnictwo Techniczne: Katowice, Poland, 1995.
- Whittow, J. *Dictionary of Physical Geography*; Penguin Books: Great Britain, UK, 1986; p. 591.
- Wigley, T.M.L.; Brown, M.C. The Physic of Caves. In *The Science of Speleology*; Ford, T.D., Cullingford, C.H.D., Eds.; Academic Press: Cambridge, MA, USA, 1976.
- Thomas, D.W. Hibernating bats are sensitive to nontactile human disturbance. *J. Mammal.* **1995**, *76*, 940–946. [\[CrossRef\]](#)

18. Thomas, D.W. The physiological ecology of hibernation in vespertilionid bats. *Symp. Zool. Soc. Lond.* **1995**, *67*, 219–231.
19. Turbill, C.; Bieber, C.; Ruf, T. Hibernation is associated with increased survival and the evolution of slow life histories among mammals. *Proc. R. Soc. B Biol. Sci.* **2011**, *278*, 3355–3363. [\[CrossRef\]](#)
20. Zubait, A.; McCracken, G.F.; Kunz, T.H. *Functional and Evolutionary Ecology of Bats*; Oxford University Press: New York, NY, USA, 2006.
21. Schmidt-Nielsen, K. *Fizjologia Zwierząt*; PWN: Warszawa, Poland, 2008.
22. Boyles, J.G.; Johnson, J.S.; Blomberg, A.; Lilley, T.M. Optimal hibernation theory. *Mammal Rev.* **2019**, *50*, 91–100. [\[CrossRef\]](#)
23. Geise, F. *Ecological Physiology of Daily Torpor and Hibernation*; Springer: Berlin/Heidelberg, Germany, 2021.
24. Koteja, P.; Jurczyszyn, M.; Wołoszyn, B. Energy balance of hibernating mouse-eared bat *Myotis myotis*: A study with a TOBEC instrument. *Acta Theriol.* **2001**, *46*, 1–12. [\[CrossRef\]](#)
25. Ransome, R. *The Natural History of Hibernating Bats*; Christopher Helm: London, UK, 1990; pp. 1–235.
26. Speakman, J.R.; Racey, P.A. Hibernation ecology of the pipistrelle bat: Energy expenditure, water requirements and mass loss, implications for survival and the function of winter emergence flights. *J. Anim. Ecol.* **1989**, *58*, 797–813. [\[CrossRef\]](#)
27. Thomas, D.W.; Dorais, M.; Bergeron, J.-M. Winter energy budgets and cost of arousals for hibernating little brown bats, *Myotis lucifugus*. *J. Mammal.* **1990**, *71*, 475–479. [\[CrossRef\]](#)
28. Harmata, W. The thermopreference of some species of bats (Chiroptera). *Acta Theriol.* **1969**, *14*, 49–62. [\[CrossRef\]](#)
29. Drenda, J. Ocena klimatycznych warunków pracy górników w polskich kopalniach węgla kamiennego i rudy miedzi. *Górnictwo I Geol.* **2012**, *7*, 19–35.
30. Waclawik, J. *Wentylacja Kopalń*; T. 1,2 Wydawnictwa Akademii Górniczo-Hutniczej: Kraków, Poland, 2010.
31. Kokurewicz, T. Ochrona nietoperzy w obszarze Natura 2000 “Nietoperek” z perspektywy 20 lat doświadczeń. In *Materiały Ogólnopolskiej Konferencji Chiropterologicznej*; Warchałowski, M., Ed.; Grunwald24: Krynica Zdrój, Poland, 2013; pp. 36–37.
32. Klys, G. Bats in the Tarnowskie Góry-Bytom Underground system. In *The Influence of Environmental Conditions on the Bat Hibernaculum Choice*; Klys, G., Wołoszyn, B.W., Jagt-Yazykova, E., Kuśnierz, A., Eds.; ZPW Plik: Bytom, Poland, 2008.
33. Poczeko, P. Ciepło a życie. In *Zarys Termofizjologii Zwierząt*; Państwowe Wydawnictwo Naukowe: Warszawa, Poland, 1990.
34. Kowalski, K.; Ruprecht, L. Rząd nietoperze. In *Klucz Dooznaczania Ssaków Polski*; Pucek, Z., Ed.; Państwowe Wydawnictwo Naukowe: Warszawa, Poland, 1984; pp. 85–139.
35. Henshaw, R.E.; Folk, G.E. Relation of thermoregulation to seasonally changing microclimate in two species of bats *Myotis lucifugus* and *M. sodalis*. *Physiol. Zool.* **1966**, *39*, 223–236. [\[CrossRef\]](#)
36. McNab, B.K. The behavior of temperature cave bats in a subtropical environment. *Ecology* **1974**, *55*, 943–958. [\[CrossRef\]](#)
37. McNab, B.K. Evolutionary alternatives in the physiological ecology of bats. In *Ecology of Bats*; Kunz, T.H., Ed.; Plenum Press: New York, NY, USA; London, UK, 1982; pp. 151–200.
38. Bohdal, T.; Charun, H. *Zasady Transportu Ciepła*, cz. 2; Wydawnictwo Uczelniane Politechniki Koszalińskiej: Koszalin, Poland, 2013.
39. Harrie, C. Etho-ökologische Untersuchung der ganzjährigen Aktivität von Wasserfledermäusen (*Myotis daubentoni* Kuhl, 1819) am Winterquartier. *Mitteilungen Naturwissenschaftlichen Ges. Schaffhausen* **1994**, *39*, 15–52.
40. Pistole, D.H. Sexual differences in the annual lipid cycle of the big Brown bat *Eptesicus fuscus*. *Can. J. Zool.* **1988**, *67*, 1891–1894. [\[CrossRef\]](#)
41. Hayman, D.T.S.; Cryan, P.M.; Fricker, P.D.; Dannemiller, N.G. Long-term video surveillance and automated analyses reveal arousal patterns in groups of hibernating bats. *Methods Ecol. Evol.* **2017**, *8*, 1813–1821. [\[CrossRef\]](#)
42. Cheng, T.L.; Gerson, A.; Moore, M.S.; Reichard, J.D.; DeSimone, J.; Willis, C.K.R.; Frick, W.F.; Kilpatrick, A.M. Higher fat stores contribute to persistence of little brown bat populations with white-nose syndrome. *J. Anim. Ecol.* **2019**, *88*, 591–600. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Bachorec, E.; Bartonicka, T.; Heger, T.; Pikula, J.; Zukal, J. Cold arousal—A mechanism used by hibernating bats to reduce the energetic costs of disturbance. *J. Therm. Biol.* **2021**, *101*, 103–107. [\[CrossRef\]](#)
44. Johnson, H.E.; Lewis, D.L.; Verzuh, T.L.; Wallace, C.F.; Much, R.M.; Willmarth, L.K.; Breck, S.W. Human development and climate affect hibernation in a large carnivore with implications for human–carnivore conflicts. *J. Appl. Ecol.* **2017**, *55*, 663–672. [\[CrossRef\]](#)
45. Nagel, A.; Nagel, R. How do bats choose optimal hibernation temperatures for hibernation? *Comp. Bio-Chem. Physiol.* **1991**, *99A*, 323–326. [\[CrossRef\]](#)
46. Klüg-Baerwald, J.; Gower, L.E.; Lausen, C.L.; Brigham, R.M. Environmental correlates and energetics of winter flight by bats in southern Alberta, Canada. *Can. J. Zool.* **2016**, *94*, 829–836. [\[CrossRef\]](#)
47. Bogdanowicz, W. Community structure and interspecific interactions in bats hibernating in Poznań. *Acta Theriol.* **1983**, *28*, 357–370. [\[CrossRef\]](#)
48. Bogdanowicz, W.; Urbańczyk, Z. Some ecological aspects of bats hibernating in city of Poznań. *Acta Theriol.* **1983**, *28*, 371–385. [\[CrossRef\]](#)
49. Daan, S.; Wichers, H.J. Habitat selection of bats hibernating in a limestone cave. *Z. Säugetierk.* **1968**, *33*, 262–287.
50. Harmata, W. Nietoperze zimujące w fortyfikacjach twierdzy Kraków. In *Zimowe Spisy Nietoperzy w Polsce 1988–1992. Wyniki i Ocena Skuteczności*; Wołoszyn, B.W., Ed.; Publikacje Centrum Informacji Chiropterologicznej ISEZ PAN Kraków: Warszawa, Poland, 1994; pp. 69–90.
51. Lesiński, G. Ecology of bats hibernating underground in Central Poland. *Acta Theriol.* **1986**, *31*, 507–521. [\[CrossRef\]](#)

52. Webb, P.I.; Speakman, J.R.; Racey, P. How hot is a hibernaculum? A review of the temperatures at which bats hibernate. *Can. J. Zool.* **1996**, *74*, 761–765. [[CrossRef](#)]
53. Boyles, J.G.; Boyles, E.; Dunlap, R.K.; Johnson, S.A.; Brack, V. Long-term microclimate measurements add further evidence that there is no “optimal” temperature for bat hibernation. *Mamm. Biol.* **2017**, *86*, 9–16. [[CrossRef](#)]
54. Humphries, M.M.; Kramer, D.L.; Thomas, D.W. The Role of Energy Availability in Mammalian Hibernation: An Experimental Test in Free-Ranging Eastern Chipmunks. *Physiol. Biochem. Zool.* **2003**, *76*, 180–186. [[CrossRef](#)]
55. Nowack, J.; Levesque, D.L.; Reher, S.; Dausmann, K.H. Variable Climates Lead to Varying Phenotypes: “Weird” Mammalian Torpor and Lessons from Non-Holarctic Species. *Front. Ecol. Evol.* **2020**, *8*, 60. [[CrossRef](#)]
56. Nedergaard, J.; Cannon, B. Mammalian hibernation. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **1990**, *326*, 669–986.
57. Thomas, D.W.; Geiser, F. Periodic arousals in hibernating mammals: Is evaporative water loss involved? *Funct. Ecol.* **1997**, *11*, 585–591. [[CrossRef](#)]
58. Wojciechowski, M.S.; Jefimow, M.; Tęgowska, E. Environmental conditions, rather than season, determine torpor use and temperature selection in large mouse-eared bats (*Myotis myotis*). *Comp. Biochem. Physiol.* **2007**, *147A*, 828–840. [[CrossRef](#)]
59. McGuire, L.P.; Mayberry, H.W.; Willis, C.K. White-nose syndrome increases torpid metabolic rate and evaporative water loss in hibernating bats. *Am. J. Physiol.-Regul. Integr. Comp. Physiol.* **2017**, *313*, R680–R686. [[CrossRef](#)] [[PubMed](#)]
60. Thomas, D.W.; Cloutier, D. Evaporative water by hibernating little brown bats, *Myotis lucifugus*. *Physiol. Zool.* **1992**, *65*, 443–456. [[CrossRef](#)]
61. Speakman, J.R. Position of the pinnae and thermoregulatory status in little brown bats (*Plecotus auritus*). *J. Therm. Biol.* **1988**, *13*, 25–29. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.