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Attenuating Anthropogenic Impact on Subterranean Micro-Climate: Insights from the Biospeleological Station in Postojna Cave

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Abstract: The Biospeleological Station (BS) in Postojna Cave, with a volume of 36,000 m^3, has served as an underground biological laboratory since 1931, receiving 100,000 visitors annually. Historical cave micro-climate monitoring was performed in 1933 and 1963, and continuous monitoring of cave air temperature and carbon dioxide concentration at hourly intervals started in 2015. Micro-climatic data collected between 2015 and 2024 has helped us to understand the relationship between natural underground environment and anthropogenic impact, thereby aiding expert recommendations to cave managers for the mitigation of anthropogenic micro-climatic effects. Results strongly support the policy that, during summer, when outdoor temperatures are higher than in the cave, solid metal doors connecting the BS with the rest of the cave (Stara Jama) should be kept open. Such a simple mitigation act helps to decrease anthropogenically increased air temperature and carbon dioxide concentrations, thereby maintaining suitable micro-climatic conditions for the exhibition of cave animals. Closure during the COVID-19 pandemic (2020–2021) resulted in the lowest temperatures recorded. BS visitation increases air temperature by 1 °C, highlighting the need for management strategies to maintain suitable conditions for cave fauna exhibition.

Keywords: air temperature; carbon dioxide; show cave; sustainable management; COVID-19 pandemic; Dinaric karst; Slovenia

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1. Introduction

Postojna Cave is the most visited show cave in Slovenia and probably one of the most visited in the world. In 2023 it received 826,000 visitors. The cave has welcomed 41.59 million visitors since 1819, receiving 826,000 in 2023 alone, and it has been under careful examination in regard to the impacts of visitors on the cave environment since 2009 [1–3]. A small entrance chamber called the Biospeleological Station (BS) is open for tourist visits separately from the rest of the cave. This passage was discovered in 1818 and opened in 1931 as an underground biological station with aquariums and terrariums for terrestrial and water cave fauna [4,5]. This part of the cave system receives at least 100,000 visitors per year, which generally represents 15% of the visitors to Postojna Cave.

Since 2015, micro-climatic monitoring (cave air temperature (T) and carbon dioxide concentrations) of BS have been coordinated in order to measure the impact of visitors on the small cave chamber and maintain sustainable use of this part of the cave system.

Biospeleological Station exhibits not only the regular speleological aspects of the show cave but holds additional biological (exhibition of live cave animals), historical (inscriptions on cave walls as early as 1818), paleontological (remains of *Ursus Spelaeus*) and archaeological (human Prehistoric) value. BS has three features that are important to sustainable management: (1) cave biology, (2) historic inscriptions and (3) cave atmosphere.

Studies of thermal patterns in caves are relevant for understanding the impact of climate change in subterranean ecosystems, as well as for understanding speleothem genesis and for paleoclimate reconstructions [6]. In caves that are highly susceptible to surface temperature fluctuations, climate extremes may be detected inside the cave that threaten subterranean biota and ecosystem services [6]. In the case of Postojna Cave, cave fauna is not thought to be threatened yet by climate extremes [7], although it is accepted that subterranean species are particularly sensitive to climate change, and there is the urgent need for future research, monitoring programs and conservation measures [8].

The transfer of heat in cave air is controlled by convection [9]. In the case of the Pertosa−Auletta show cave (SW Italy) researchers investigated the temporal and spatial scales of tourism-induced micro-climatic alterations through monitoring [10], showing that the impacts of 60,000 visitors per year integrated within natural fluctuations, as the tourism-induced alterations decayed quickly in space and time [10].

Decrease in humidity can lead to a decline in cave-adapted animal life. Increase in CO_2 concentration in a cave can lead to dissolution of cave formations. Condensation can cause corrosion of cave walls or formations; thus, monitoring in caves helps to assess risk to resources [11].

Tourists in Slovenia prefer geosites without major tourism infrastructures and pay more attention to the protection of these sites. The leading geotourism role of the Postojna Cave and Škocjan Caves has been proven [12].

Tourist visits to Postojna Cave increased microbial concentrations from 1.2 to 10.2 times the concentration measured before tourist visitation [3]. Higher microbial concentrations have been associated with tourist visitation but not with number of tourists, with the highest numbers of cultivable microorganisms in the BS being observed in May 2017 and November 2018 [3], dates that do not correspond to its periods of highest visitation.

Mass tourism in caves significantly changes the composition of the aerosol, yielding higher total concentrations of airborne microorganisms and a high number of species typical of the human microbiota [3].

Temperature fluctuations in the air are greater than that of the limestone due to the greater thermal capacity of the rock than that of the air. The resulting condensation is responsible for changes to multiple wall states in caves [9]. Caves with famous rock art are subject to micro-climate studies to better understand the conditions for preserving the art [9]. The morphology of Leye Cave (Dordogne, France) forms a cold air trap which results in the phenomenon of condensation corrosion, which in turn impacts the cave walls and degrades the rock art on them [9].

Caves are recognized as valuable »natural laboratories« [13]. Vulnerability maps by season have been proposed in the case of four Romanian show caves, to be classified as having reduced, medium, high, or very high vulnerability [13].

Reaching the state in which anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals (net zero CO_2 emissions) is a key milestone for a safer planet [14].

The objectives of the study presented here were as follows:

- To comprehensively characterize the micro-climate within the Biospeleological Station (BS), a confined chamber within the voluminous Postojna Cave, located proximate to its entrance.
- To systematically gather continuous, long-term data on micro-climatic parameters, specifically air temperature and carbon dioxide concentration, from multiple monitoring sites within the BS.
- To analyze and evaluate the impact of visitor activity on the environmental conditions within the BS.
- To propose and recommend mitigation measures aimed at preserving the Biospeleological Station's ecological integrity and ensuring its sustainable use, particularly in the face of alterations to its micro-climate and overall environment induced by mass tourism visitation.

2. Study Location and Methods

Biospeleological Station (BS, a small passage of Postojna Cave) has a ground plan that is 90 m long, 10 m wide and up to 10 m high, with a volume of 36,000 m^3. The Vivarium (the southern part of the BS where visits are organized, Figure 1—gray color) has a volume of 18,000 m^3. In the speleological sense the entire passage of BS is 220 m long and is situated 20–30 m below ground surface [15]. The passage was discovered in 1818 and accessed from the north by way of the Stara Jama passage (Figure 1). Cave sediments that had blocked the southern entrance to BS were removed during construction of an underground railway, probably between 1921 and 1925. In 1964 and 1969 there were archaeological excavations [16] that found cultural layers of Mousterian Culture [17]. Paleolithic humans (roughly from 160,000 to 40,000 BP) had entered through the natural cave entrance at the southern end of BS, which was later closed by cave sediments until the period of 1918–1941. In 2002, modern entrance doors were constructed for the BS at its southern side with the purpose of allowing visitors to access BS separately from the rest of the cave.

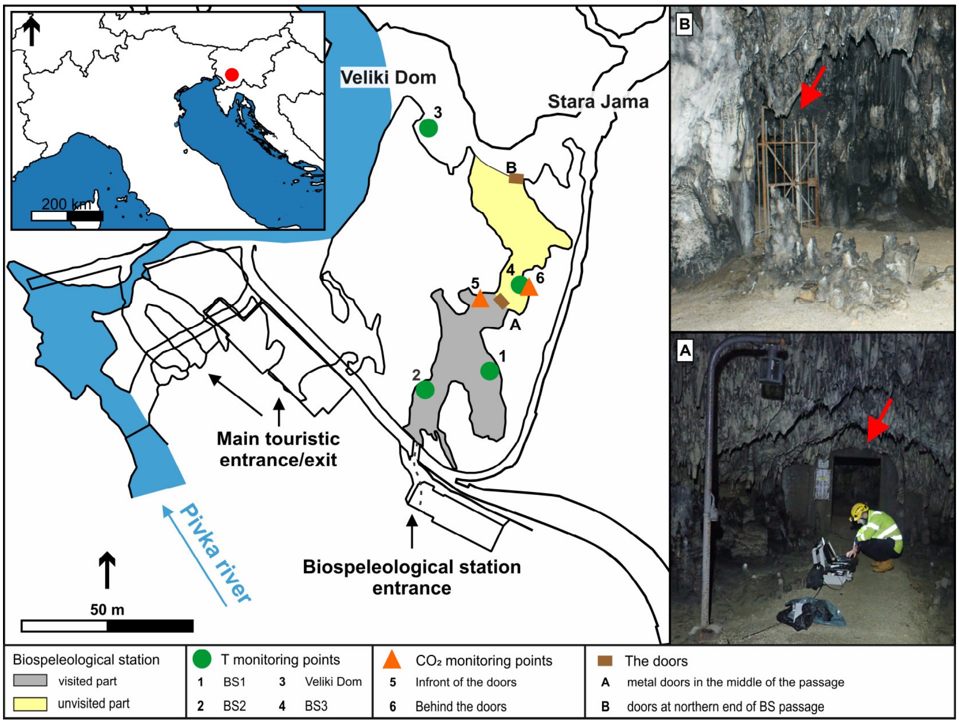

Figure 1. Ground plan of Biospeleological Station (BS; yellow and gray) within the Postojna Cave (Slovenia) with micro-climatic monitoring sites. Red circle in the upper left figure represents location of Postojna Cave with BS within the Slovenia in Europe. Green circles represent air T monitoring points; (1) BS2, (2) BS1, (3) Veliki Dom, (4) BS3, (5) Carbon dioxide monitoring site, (6) Carbon dioxide monitoring site behind the doors. Orange triangles represent carbon dioxide monitoring points. Brown polygons represent doors (**A**) metal doors in the middle of the passage, red arrow points to the doors, (**B**) doors at northern end of BS passage, red arrow points to the doors. Gray color represents a touristic part of BS that is also called the Vivarium.

Air T monitoring was set up in BS on 13 March 2015 at two locations (BS1 and BS2, Figure 1). CO_2 monitoring was also set up in BS on the same day (Figure 1 number 5). A third air T monitoring site BS3 and second CO_2 monitoring site (behind (north from) the doors, Figure 1, numbers 4 and 6) were set up at the end of 2016 until the end of 2018 to investigate the influence of the opening of the metal doors on the cave microclimate on both sides of the doors. In addition to the BS measuring points, the air T measuring point at Veliki Dom (Site 3, Figure 1) and an air T measuring point outside Postojna Cave (located in the forest on the surface about 2 km North from BS locations) were used for microclimatic interpretations.

Closed metal doors in the middle of the BS passage (Figure 1A) prevent air circulation the northern part of BS, but doors at the northern end of the BS passage (Figure 1B) are not solid and do not prevent air circulation, as their intention is only to prevent undesirable visits.

The measurement intervals for T and CO_2 are 1 h at all locations. Air T was measured with Baro-Diver® data loggers (Van Essen Instruments, Delft, The Netherlands) with an accuracy of ±0.1° and a resolution of ±0.01°. CO_2 concentrations were measured using the MI70 measurement indicator and the CARBOCAP® carbon dioxide probe GMP252 from Vaisala Oyj (Vantaa, Finland) with an operating temperature ranging from −40 to +60 °C and a measurement range between 0 and 10,000 ppm CO_2.

The T and CO_2 datasets were analyzed by graphical interpretations at 24 h intervals, 1 h intervals, and annual averages. The cave measurements were compared with the outside cave air T and the number of visitors per year.

3. Results and Discussions

3.1. Air Temperature Monitoring

The air T in the BS shows seasonal and daily variations, showing the influence of the outside air T on the cave T due to the close proximity of the cave entrance and the opening of the doors for tourist visits. There is also a temporal shift of 1–1.5 months for T inside the cave with respect to T outside (Figure 2). The daily fluctuations are mostly due to the presence of visitors. In 2019, the year with the most visitors, the daily oscillation on August 5 at Station BS1 was 0.83 °C, while, on the same date in 2020, it was 0.39 °C. The air temperature on 5 August 2020 was 0.9 °C lower than on 5 August 2019. This difference is attributed to the COVID-19 pandemic, which resulted in decreased visitation in 2020. Additionally, at Nerja Cave (Spain), closure of the cave during COVID-19 provided a unique opportunity to study the micro-climate conditions and carbonate precipitation without the presence of visitors [18].

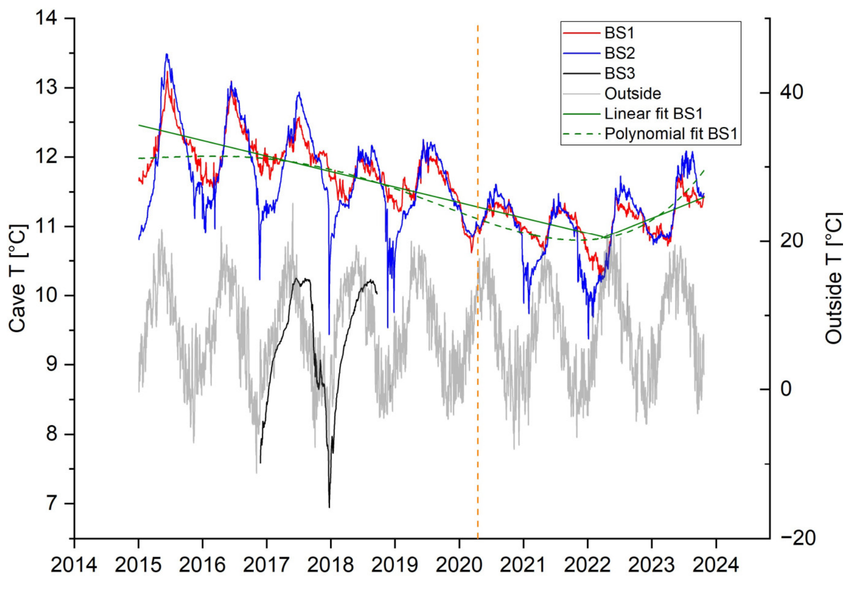

Figure 2. Air T (°C) at Biospeleological Station (BS) locations compared to outside air T for the period 2015–2024 with 24 h interval. The vertical dashed orange line represents the start of COVID-19 pandemic period.

In general, the air T at BS1 has more stable values over a year than at BS2, which is closer to the cave entrance and is more strongly influenced by cold winter air and warm summer air from outside. In cold winters, the air T at Station BS2 can drop by up to 3 °C and reach 7.5 °C, as it is located close to the entrance doors. The air temperature at Station BS 1 was always higher than 10.14 °C (2015–2024). Station BS3 (Figure 1, number 4) had a lower air temperature than Stations BS1 and BS2, as it is more influenced by the cave ventilation through the main entrance and the main passages of the cave system.

Over the measurement period, air T at sites BS1 and BS2 were highest in 2015 because the solid metal doors in the middle of the passage leading to the rest of the cave were kept closed. Following our suggestion to the cave management to leave the doors open all year round, the air temperature dropped, with the lowest values occurring in 2020 and 2021 when fewer visitors came due to the COVID-19 pandemic. With the return of visitors to the cave, the air temperature began to rise again in 2022, and by 2023 it was similar to 2018. The linear trend of temperature drop at BS1 from 2015 to the spring of 2022, when the touristic activity started to recover from the COVID-19 pandemic, is −0.21 °C per year. The rising trend after Spring 2022 is 0.36 °C per year (Figure 2).

In a similar study, it was shown that a group of 5–6 people spending 6–8 h per day in a medium-sized cave gallery (~6 × 1.5 m) triggered a temperature increase of about 0.5 °C after only 1–2 days. The period of return to the initial state was usually 1–3 days [13]. The researchers found that, with many visitors in a similar-sized cave room, air T rise could exceed 0.5–1 °C [13].

The period of the COVID-19 pandemic meant that Postojna Cave, including BS, was closed from 13 March to 2 June 2020 and from 26 October 2020 to 9 June 2021. Comparing these periods with the most visited year of 2019 (Figure 3), it can be seen that the air T in 2020 and 2021 was lower than in 2019. At BS 1, the air temperature in March–June 2020 and March–June 2021 was about 0.7 °C lower than in March–June 2019 (Figure 3) and in October–December 2020 and 2021 it was about 0.35 °C lower than in 2019. In 2019, the daily air T fluctuations at the BS in March–June were up to 0.3 °C, which must be attributed to visitors, as the daily fluctuations in March–June 2020 and 2021 in the period without people are within the order of magnitude of the instrument accuracy. The last weeks of 2019 and 2021 (Figure 3) show an increase in temperature at the BS1 site due to higher visitor numbers during the Christmas−New Year holidays. In the same period in 2020, the cave was closed and temperature increase did not take place.

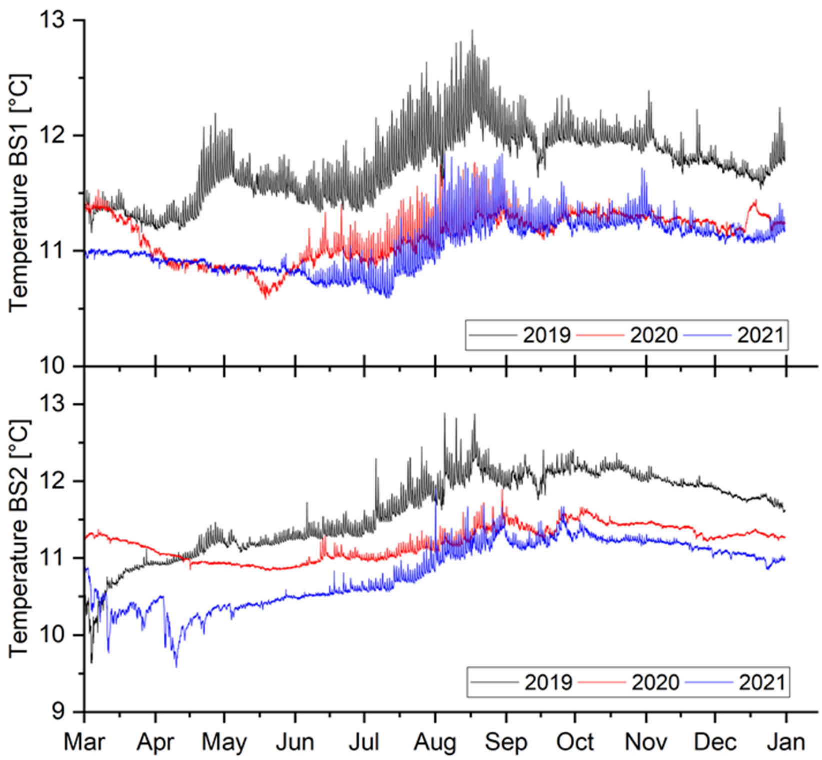

Figure 3. Comparison of cave air T at BS1 and BS2 (in °C) from 1 March to 31 December for years 2019, 2020 and 2021 at 1 h intervals.

The summer period (June–end of September) results in similar daily fluctuations for all three years 2019–2021, with maximum values of up to 0.9 °C, but the base of the air T curve is around 1 °C lower in 2020 and 2021 than in 2019 (Figure 4). This means that a high number of visitors to BS increases the air temperature by at least 1 °C.

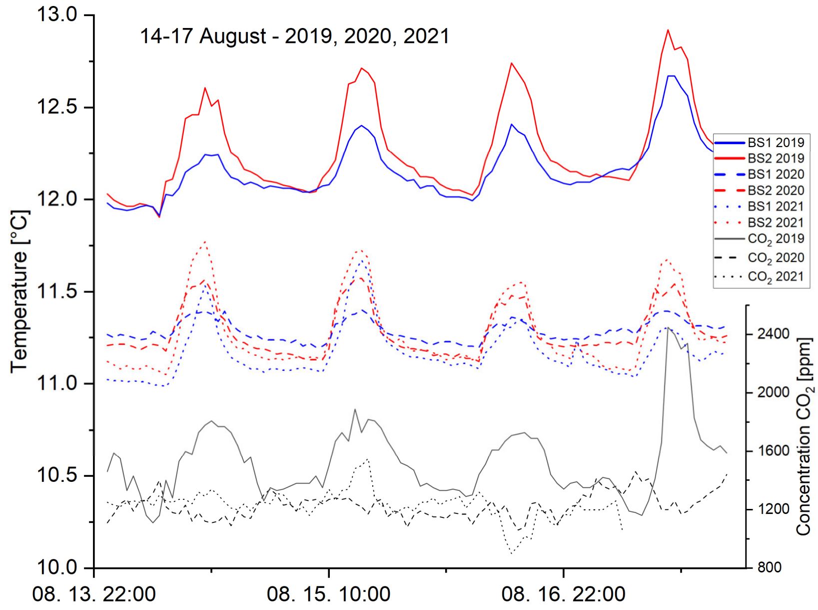

Figure 4. Comparison of air T (in °C) and CO_2 (in ppm) at BS from 14–17 August (2019, 2020 and 2021). Due to instrument problems, CO_2 was not measured on 17 August 2021.

3.2. Carbon Dioxide Monitoring

At the beginning of the monitoring period in Summer 2015, CO_2 concentrations reached up to 4200 ppm during the peak season (Figure 5). In 2015, visitation of about 100,000 tourists inside a volume of approximately 18,000 m^3 with closed doors caused the highest concentrations over the entire monitoring period (2015–2024), consisting of natural and anthropogenic sources. After the mitigation was enacted (forced ventilation due to door opening), we no longer reached such high levels.

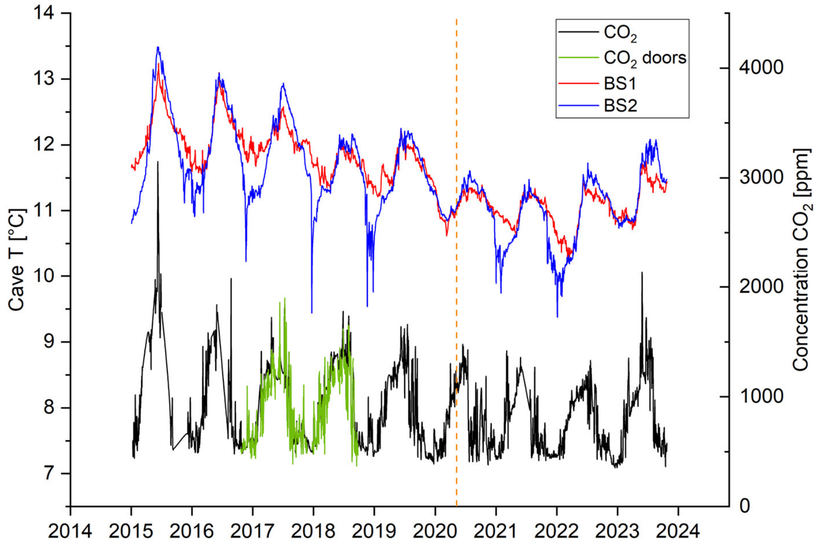

Figure 5. Air T (in °C) and CO_2 (in ppm) at BS for the period 2015–2024, 24 h intervals. The vertical dashed orange line represents start of COVID-19 pandemic period.

In 2017−2018, CO_2 concentrations behind the door (with the door open, numbers 4 and 6 of Figure 1) were very similar to values at the measurement point inside the passageway. This finding confirmed the efficacy of the mitigation measure.

The CO_2 concentrations in the BS show higher values in warmer periods than in colder periods, which is typical for Postojna Cave [19]. In winter, the CO_2 concentration of the air in BS is reduced to the level of the outside air (~500 ppm) by intensive ventilation. In summer, CO_2 concentrations in the BS are higher ($CO_{2(min)} \approx 1100$ ppm and $CO_{2(max)} \approx 2300$ ppm in 2019) as the ventilation rate is not as high as in winter and the outside air entering the cave is enriched with soil-sourced CO_2 that is released during this season. Human respiration in the BS can account for up to 1000 ppm CO_2 per day on a summer day during the peak touristic season.

During the COVID-19 pandemic in 2020 and 2021, there was a detectable shift in CO_2 concentrations, generally registering at lower levels (200–300 ppm) compared to periods of heightened visitor activity. This subtle observation adds anthropogenic concentrations to the natural background of CO_2 levels.

In Romanian show caves, immediate increases of CO_2 concentrations were observed in the periods aligning with national holidays, which hosted higher visitor numbers [13]. A comparable trend is observed at BS (Figure 4).

3.3. Comparison of Past and Present Data in Relation to Visitor Dynamics

In 1933, historical air T measurements were carried out at the BS1 site for one year [20]. Later, in 1963, Gams [21] carried out sporadic measurements at BS1. The mean annual air T values at BS1 and BS2 are consistently higher (by 1.5 to 2 °C) than the mean annual outdoor air T values for the period 2015–2024 (Figure 6), indicating an anthropogenic warming of the microclimate in BS.

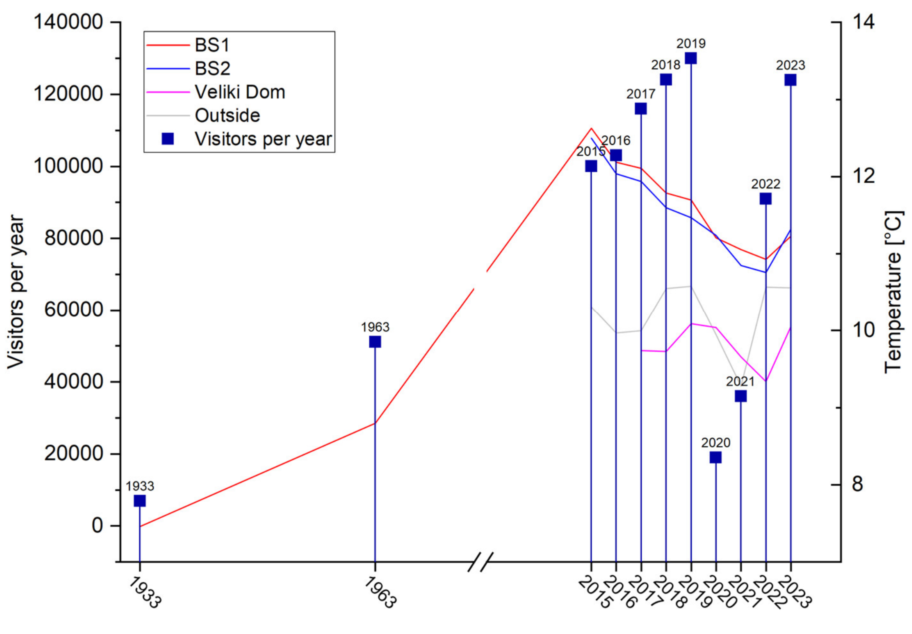

Figure 6. Mean annual air T in °C for cave sites (BS1, BS2, and Veliki Dom) comparing to the mean annual outside cave air T and the number of visitors to BS per year.

Anthropogenic warming, representing heat emitted to the cave atmosphere by visitors, is also demonstrated by correspondence of the decrease in visitor numbers in 2020 and 2021 (COVID-19 period) to a decrease in mean annual cave air T, as well as the increase in visitor numbers in 2022 and 2023 to an increase in mean annual air T. In the sense that the mean cave air T in temperate climates reflects the mean outdoor air T [22], we see that this is not the case for BS, where the anthropogenic influence is strong. This difference is confirmed by the values for the mean annual air T (2017–2024) at the Veliki Dom monitoring site (Figure 6), which are not as high as in BS and correspond more closely to the outdoor values.

The Veliki Dom measuring point (number 3, Figure 1) is strongly subjected to surface conditions. While human impact is present [23], it is not so strongly expressed because the space is more voluminous than BS and has a stronger ventilation connection to the outside. The average monthly temperatures measured in the deeper part of Postojna Cave (Sepolcro site) in the modern period (2016–2019) are significantly higher than in the historical period (1935–1937), with the largest difference being of +2.12 °C in October [23]. In the case of BS, the difference seems to be even larger, as it is about 2–3 °C lower in the period 1933–1963 than in the period 2015–2024. This is probably due to the high number of visitors (up to 130,000 per year) in a small chamber (18,000 m^3), as well as the fact that the access doors were kept closed before 2015, which restricted ventilation with the rest of the cave system. Additionally, the outside temperature rise was also a factor [23].

3.4. Sustainable Use of Biospeleological Station

As BS is a show cave, since its discovery in 1818, various constructions have been made in terms of artificial openings, walls and doors. The introduction of modern microclimatic monitoring in 2015 was the basis for understanding the natural and/or anthropogenic influences on this small part of Postojna Cave [2,3].

Cave tourism is expected to increase, especially in countries where caves are abundant but not yet considered to be tourist attractions. Their management needs to be sustainable so that the caves become a base of sustainable local economies, educating people on these fragile geo- and ecosystems, and protecting their scientific and cultural heritage for future generations [24].

Every show cave holds unique aspects and, therefore, the management entities need to select the practices that best fit their particular situation and to continuously adapt them to changing conditions [25]. Sustainable management of a show cave should be seen as a process that its management entities should work on continuously [25].

Scheduled guided tours are not arranged at the BS, as only self-guided tours are available. Visiting hours are from 9:00 to 17:00 during the summer season and from 10:00 to 15:00 during winter. On average, a tourist spends about 1 h at BS. Lighting (which is not very strong in order to protect cave animals) within the BS is activated only in the presence of people, thereby resulting in extended lighting periods during peak visitation. At BS, the electric power of lamps or the resulting heat flow is not measured; therefore, it cannot be determined how much heat is being emitted to the cave atmosphere from lighting in addition to human presence. At the aforementioned Romanian cave, an experiment with lighting in the absence of tourist activity yielded a quick thermal response consisting of a temperature increase ranging from 0.1 to 0.2 °C, with normal temperature levels being reestablished after approximately 10 h [13].

An experiment can potentially be carried out by cave management where limited tourist groups (between 20 and 30) could enter BS for no more than 30–40 min with an approximately 15–30 min break between groups. In such a way, a comparison of different visits regimes can be made, and it can be evaluated which visit regime had less impact on cave micro-climate.

Results obtained from micro-climatic monitoring at BS since 2015 strongly support the practice that, during summer ($T_{out} > T_{cave}$), the metal doors connecting BS with the rest of the cave (Stara Jama) must remain open. Such a straightforward intervention strategy serves to mitigate anthropogenically induced higher thermal and carbon dioxide concentrations, maintaining a suitable microclimate for the exhibition of cave animals and the overall natural cave environment.

Despite the considerable influx of visitors to BS within the confines of a fairly small chamber, deposition of flowstone upon a glass substrate in the BS measuring 61 × 18 cm registers an average growth rate of 0.11 mm per year [26], indicating that flowstone formation processes are ongoing. Furthermore, in 2016 [27] offspring hatched from the eggs of the human fish (*Proteus anguinus*), which is a testament to BS remaining a suitable environment for cave fauna. However, in the eventuality of drastic increases in air T, CO_2 and visitor numbers in future years, mitigation steps related to visitations and re-organization of visits should be considered. In this sense, micro-climatic and biological monitoring at BS must be continued.

4. Conclusions

In conclusion, our findings from hourly air temperature (T) and carbon dioxide (CO_2) monitoring, conducted since 2015 at various locations within the Biospeleological Station (BS), a small entrance chamber of the Postojna Cave with a volume of 18,000 m^3 specifically designated for tourist visitation, have provided valuable insights into the sustainable management of cave tourism:

- During the summer of 2015, maximum CO_2 levels reaching up to 4200 ppm were observed, correlating with peak visitor activity and the closure of internal metal doors within the cave. Our recommendation to hold these doors open, facilitating forced ventilation with other areas of the cave system, proved effective in mitigating anthropogenic impacts on air temperature and CO_2 concentrations inside the chamber, thereby preserving a suitable microclimate for the exhibition of cave fauna.
- Analysis of air temperature data at BS revealed two notable temperature drops. The first occurred between 2015 and 2019 and is attributed to the implementation of door opening practices. The second drop, observed between 2020 and 2022, coincided with the COVID-19 pandemic period, during which the cave was closed to visitors for nearly 11 months.
- Air temperatures in the chamber during the COVID-19 pandemic years of 2020 and 2021 were approximately 1 °C lower compared to 2019, the year with the highest visitor influx. This difference highlights the significant impact of visitor numbers on air temperature, with high visitation contributing to temperatures being elevated by at least 1 °C.
- CO_2 concentrations during the COVID-19 pandemic years were generally lower (ranging from 200 to 300 ppm) compared to years with high visitor traffic, indicating anthropogenic contributions to natural CO_2 levels.
- Mean annual air temperature values in BS consistently exceeded those of the surrounding outdoor environment by 1.5−2 °C throughout the monitoring period from 2015 to 2024, indicative of anthropogenically induced heat affecting the microclimate of BS.
- Historical comparisons of air temperature measurements from 1933 and 1963 to the modern monitoring period (2015–2024) revealed a notable increase of 2–3 °C in modern times. This escalation is attributed to both high visitor numbers within a confined chamber and the previous closure of the solid metal doors at BS, blocking ventilation in the rest of the cave system prior to 2015, as well as outside temperature rise [23].
- Our findings emphasize the importance of independent, sustained environmental monitoring in smaller chambers of larger cave systems, particularly when these chambers are developed as show caves with distinctive tourist offerings.

In summary, our comprehensive environmental monitoring efforts at the Biospeleological Station have provided crucial insights into the sustainable management of cave tourism, highlighting the effectiveness of simple mitigation measures and the significant influence of visitor activity on cave microclimates. These findings are essential for informing future management strategies aimed at preserving the ecological integrity of cave ecosystems while facilitating responsible tourism practices.

Author Contributions: Conceptualization, S.Š. and U.N.; methodology, S.Š. and U.N.; formal analysis, S.Š. and U.N.; investigation, S.Š. and U.N.; data curation, S.Š. and U.N.; Writing—Original draft preparation, S.Š. and U.N.; Writing—Review and editing, S.Š. and U.N. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All the data is available upon request.

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

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