Abstract: Waitomo Glowworm Cave is a highly visited cave where the highlight is viewing the bioluminescence display of a large colony of glowworms. Anthropogenic carbon dioxide build-up in the cave is prevented by management of chimney-effect ventilation aided by a network of microclimate sensors. A cave door prevents ventilation under drying conditions and promotes it when necessary to clear CO$_2$ and when inflowing air has high relative humidity. A COVID-19-related nationwide “lockdown” in New Zealand from March 2020 resulted in neither staff nor visitors being present in the cave for 60 days, and provided an opportunity to assess the natural microclimate of the cave, especially the natural variation in partial pressure of carbon dioxide (pCO$_2$). In addition, comparison to the previous year showed that the presence of people in the cave increased the cave temperatures but the effect was short-lived due to cave ventilation. During the period of lockdown, the daily increase of carbon dioxide partial pressure (pCO$_2$) due to visitors was absent. When the cave door remained sealed, pCO$_2$ varied and tended to lie at levels above that of the external atmosphere (410 ppm). Notably, rain events raised pCO$_2$ by up to 200 ppm (v/v), which appeared to be sourced from both stream water and drip water. These natural CO$_2$ sources rarely reached the levels associated with cave visitation. The results support current management practices that use door control to enhance cave ventilation when people are in the cave or when natural conditions (high stream levels and high drip-water levels) promote CO$_2$ outgassing into the cave. Suppressing ventilation outside of those times reduces the risk of introducing dry air that could desiccate the glowworms.

Keywords: COVID-19, cave microclimate, chimney effect, carbon dioxide, Arachnocampa luminosa

population.

Given the relatively small size of the cave and the many visitors, build-up of anthropogenic CO$_2$ has been recognised as a problem since visitor numbers began to rise in the 1970s (Kermode, 1977; Kermode, 1979). High CO$_2$ levels can induce condensation corrosion in speleothems, causing irreparable damage, which appears to have occurred at some locations in Waitomo glowworm Cave (White et al., 2021). The chimney-effect cave ventilation—upflow or downflow depending on the air density gradient between upper and lower entrances—clears CO$_2$ by introducing fresh air into the cave (de Freitas, 2010). When the upper door is open, air flows freely according to the prevailing density difference of air between the upper and lower entrances: when closed, airflow is restricted. While airflow in either direction introduces fresh air, lowering the pCO$_2$, it is preferable to reduce upward airflow because it draws cool dry air into the cave creating evaporating conditions (de Freitas & Schmekal, 2003) that place desiccation stress on the larvae in the Glowworm Grotto (Pugsley, 1984). In addition, strong airflow tangles the larval fishing lines, causing the larvae to spend more time removing tangled lines and secreting new lines. They produce shorter, presumably less effective, lines when exposed to air currents (Meyer-Rochow, 2007).

Cave microclimate management has evolved with the aid of microclimate monitoring (Hendy et al., 2022). The current policy is to leave the door open on days when external temperature is higher than cave temperature (summer days) when air tends to flow downward, facilitating CO$_2$ clearance and promoting condensation on the cave internal surfaces. On days when external temperature is lower than cave temperature (winter days) when air tends to flow upward, the door is closed other than for visitor entry, preventing entry of dry air that could warm and evaporate moisture from cave surfaces and the glowworm fishing lines. Outside of visiting hours, the door is automatically managed to stay open until the internally monitored pCO$_2$ drops below 800 ppm (Hendy et al., 2022); whereupon it closes until visits begin the next day.

It has been noted that on rare occasions pCO$_2$ has risen in the absence of any significant anthropogenic inputs, often in association with rainfall and/or flooding of the Waitomo Stream. Both the Waitomo Stream and drip waters contributed to the CO$_2$ in the cave atmosphere (Miedema, 2009). The nationwide restriction of movement to combat the COVID-19 pandemic which began in New Zealand on March 25th 2020 resulted in a complete absence of people in Glowworm Cave for approximately seven weeks. This presented an opportunity to observe the non-anthropogenic behaviour of the cave climate in the absence of people under different door management conditions.

**METHODS**

Temperature and humidity were monitored in three chambers within Glowworm Cave, partial pressure of CO$_2$ was monitored in two chambers, airflow was monitored near the cave upper entrance and water depth and temperature were monitored in the Waitomo Stream within the Glowworm Grotto. The names of the Glowworm Cave chambers and locations of sensors are shown on a cave map in Supplementary Figure S1. Temperature and relative humidity were recorded using Vaisala HMP155A temperature probes, airflow using a Young 3D ultrasonic anemometer, partial pressure of CO$_2$ in parts per million (ppm) using Vaisala Carbocap GMP222 probes, water level at the jetty using a Campbell Scientific CS451 Submersible Pressure Transducer. Temperature and humidity were logged at 30-minute intervals. Carbon dioxide (ppm), airflow and river level were logged at 10-minute intervals. A more detailed description of the monitoring instrumentation is given in Hendy et al. (2022).

**RESULTS**

**Microclimate and air movement with people present**

Tourist numbers began dropping in early February 2020, and had ceased by March 25 (Fig. 1). To demonstrate the effect of visitation on cave microclimate, we consider three 10-day periods that encompass: (1) the fall-off in visitation 20–29 Feb 2020 with daily visitation at a mean of 77% of the previous year’s attendance, (2) no visitation with door automated (23 Mar–1 Apr 2020) and (3) no visitation with door sealed (10–19 April 2020). Through these periods the temperature within three monitored chambers, the temperature differential between Tomo/Banquet and outside of the cave upper entrance, airflow in m/sec measured in the main airflow path near the upper entrance, and pCO$_2$ at the Cathedral Chamber are shown in Figures 2 and 3.

![Visitors per day](https://via.placeholder.com/150)

**Fig. 1.** Daily visitor numbers at Waitomo Glowworm Cave from 1st January to 31st May 2020.

Over the “visited” 10-day period (Fig. 2A1), the temperature at the Tomo varied consistently in accord with the external temperature on a daily cycle but over a narrower temperature range. The Tomo daily mean temperature was 17.15°C with a mean daily range of 1.85°C. By comparison, the external daily mean temperature was 18.31°C with a mean daily range of 13.41°C. The difference between the external and the cave temperature varied through the day. The external temperature crossed the internal (Tomo) temperature usually twice per day (Fig. 2B1), reversing the temperature gradient so that airflow transitioned between downward and upward (Fig. 2C1) according
to the chimney effect (de Freitas 2010). To prevent the upward flow and potentially drying conditions, the cave door was left open only during the day and for a short period into the evening, consequently airflow measured near the upper entrance is low when the door is closed at night (Fig. 2C1).

Over the 10-day period, pCO₂ monitored at the Cathedral Chamber increased substantially during the day due to anthropogenic sources (Fig. 2D1). During this period an average of 1,274 people visited per day. Tours usually started at 8:30 am and the pCO₂ reached a maximum around 11 am and fell through the afternoon due to air flowing between entrances. Over the 10 depicted days, the pCO₂ dropped to a mean minimum of 542 ± 12 ppm (mean ± standard error) soon after the door closed (Fig. 2D1). Every night during this period, the door closed at 7 pm because the pCO₂ at the Cathedral sensor was not above 800 ppm which would have triggered the door to stay open until pCO₂ of 800 ppm was reached. When ventilation was restricted by nightly door closure, pCO₂ tended to rise through the night, reaching a mean of 623 ppm ± 13 ppm immediately before door opening, indicating either a source of CO₂ within the cave or that anthropogenic CO₂ was diffusing from the distal reaches of the cave.

Microclimate with no people and scheduled, automated door opening

For the first 14 days when no people entered the cave in 2020, the door remained on an automatic cycle, opening during the day. A 10-day microclimate series (23 Mar – 1 Apr 2020) (Fig. 2A2–D2) shows that the amplitude of the diurnal temperature cycles in the chambers decreased compared to 20 – 29 Feb (Fig. 2A1). The daily mean temperature at the Tomo was 15.83°C with a mean daily range of 0.49°C. By comparison, the external daily mean temperature was 13.80°C with a mean daily range of 8.40°C. The difference between Tomo temperatures in March–April (Fig. 2A1) and in February (Fig. 2A2) is most likely due to the local weather patterns and seasonal effects rather than attributable to the absence of people (see below). In periods when outside air temperatures exceeded cave temperatures, air flowed down into the cave (negative airflow velocities) and door closure at night prevented significant upward airflow when the gradient was reversed.

The most obvious difference to the visited period is that the pCO₂ levels were substantially reduced (Fig. 2D2). The mean daily maximum pCO₂ was 550 ppm and the mean daily minimum was 427 ppm. A daily cycle was apparent as the pCO₂ decreased when the door was open and trended upwards when the door was closed. Airflow allowed ambient air (typically about 410 ppm pCO₂) to replace the cave air while the door was open (Fig. 2D2). The saw-tooth pattern of daily pCO₂ through this period is also evident in Figure 5.

Microclimate with no people and door sealed

From 9th April onwards door automation was discontinued and the door remained sealed because ventilation was seen as unnecessary in the absence of anthropogenic CO₂. As expected, little airflow was recorded (Fig. 3C) despite a more-or-less persistent daily cycle in the temperature gradient (Fig. 3B). No
persistent diurnal fluctuation pattern in pCO$_2$ was evident due to the major reduction in airflow compared to when the door was opened daily. However, the pCO$_2$ of the cave air was elevated compared to the preceding period when the door opened daily. It stabilised at around 500–600 ppm, indicating that there was a CO$_2$ source in the cave. The stream level—recorded in the Glowworm Grotto where visitors board the boats—over the same 10 days (Fig. 3E) peaked twice, reflecting two external rainfall events (13–14 April and 18–19 April). The heightened stream level was correlated with an elevation of pCO$_2$ (Fig. 3D, E).

Cave temperature with people absent

The absence of people in the cave during this period allowed a comparison with cave temperature at the same time in 2019. The temperature recorded at 30-minute intervals over 15 days of 2020 when no people were in the cave was subtracted from the same period in 2019 when 1,000 – 2,000 people visited per day (Fig. 4). It is apparent that the presence of people in the cave produced a daily air temperature spike of between 0.4 to 1.5°C at the Tomo sensor (Fig. 4). The impact was limited to approximately an hour per group and once the cave was closed to visitors each evening, the temperature returned to baseline levels. This contrasts with the approximately 700 W of electrical energy expended by the 140 five-watt LED lights that remain on from 9 am until 5 pm when the cave was open to visitors. Not only is the electrical heating small compared to the estimated 25 kW expended by 1,000 visitors per day spending one hour climbing through the cave, it is also a constant heat input and should not produce a temperature peak in the middle of the day coinciding with peak visitation.
CO$_2$ sources associated with rainfall and dripwater

The association between stream levels, rainfall recorded at a station 1.5 km from the cave, and pCO$_2$ was examined in a continuous record over 68 days from 15 Mar 2020, encompassing (1) the fall-off in visitation, (2) no visitation with door automated and (3) no visitation with door sealed (Fig. 5). The main rainfall events and associated stream level rises over the observation period are numbered 1 – 4 in Figure 5A. Event 1 occurred when the cave was still visited, extending into the period when visitation ceased. No obvious disruption of the daily pCO$_2$ pattern was evident, probably because ongoing door opening flushed any CO$_2$ arising from the event and that anthropogenic CO$_2$ overwhelmed any stream or drip-water outgassing. During period 2 with no people and automated door opening, pCO$_2$ dropped to a level close to 400 ppm each day, followed by a build-up through the night. Through 2020, the mean global atmospheric pCO$_2$ was 410 ppm and increasing (Dlugokencky & Tans, 2021) so it is apparent that door opening brought pCO$_2$ close to that of the external atmosphere. Rainfall events 2 – 4 occurred during the period when no visitors were present and the door remained closed, restricting ventilation. They resulted in stream level rises and increased pCO$_2$. Rainfall event 4 produced a spike in pCO$_2$ to 767 ppm, substantially above the global atmospheric level. The increase in pCO$_2$ associated with events 2 – 4 was initiated soon after rainfall began and before the stream level rose, suggesting that drip-water entering the cave chambers is a source of CO$_2$ along with outgassing from stream water. It is known that small headwater streams such as the Waitomo Stream that sink into caves can contain very high concentrations of dissolved CO$_2$ due to groundwater discharge from the catchment (Jones Jr & Mulholland, 1998) so the outgassing is likely due to elevated CO$_2$ in stream-water.

The pCO$_2$ levels at two different sites within the cave—the Cathedral and the Organ Loft—were examined in more detail during rainfall events 2–3 (Fig. 5B). The Cathedral site is closer to the Waitomo Stream than the Organ Loft site, which is at the end of a rarely-visited high-level side passage dominated by active speleothems, recognised as a chamber with stable temperature and low airflow that tends to accumulate CO$_2$ (de Freitas, 2010). During event 2 (April 13 – 14) the pCO$_2$ showed similar trajectories at both sites. During event 3 (16 – 18 April), the pCO$_2$ trajectory at the Organ Loft sensor did not closely track that in the Cathedral Chamber (Fig. 5B). The result suggests that during this event the dominant source of the excess carbon dioxide was outgassing from Waitomo Stream because the Cathedral sensor is located closer to the stream than the Organ Loft sensor.
DISCUSSION

Cave temperature

The absence of visitors allowed comparisons of cave temperature with and without visitors. A recent study of temperatures of different chambers of the Waitomo Glowworm Cave through the seasons and between years (Hendy et al., 2022) concluded that management of airflow in the cave did not produce progressive year-to-year warming of the cave; however, it pointed out that the temperature of the cave chambers was seasonally influenced by airflow management. That study was carried out at a time when number of visitors averaged thousands per day, so anthropogenic heat could influence chamber temperatures. Here we compared air temperature at one location, the Tomo, in the equivalent 15 day periods of 2019 (with more than 1,000 visits per day), and 2020 (with no visits). The temperature at the Tomo increased during the day when people were present (Fig. 4) with an average daily temperature spike of approximately 0.5°C. The anthropogenic temperature spike began dropping in the afternoon and temperature reached baseline, i.e. unvisited levels, by the time the cave was closed to visitors each day. While the presence of people in the cave undoubtedly raises the air temperature, microclimate management based on permitting ventilation when visitors are present soon removes anthropogenic heat, consequently speleothem development is unlikely to be substantially affected. An earlier study of cave ventilation also found that the chimney effect ventilation led to rapid recovery of temperature after people left the cave (de Freitas, 2010).

At other show caves, environmental monitoring has revealed temporary increases in temperature associated with visitors, for example at Jenolan Cave in Australia, short-lived spikes in cave temperature are associated with groups entering cave chambers (Baker, 2014). Anthropogenic heat is unlikely to affect the well-being of the glowworm larvae because larvae that are present outside the cave experience much more extreme daily temperature variation (Broadley & Stringer, 2009). Photographic monitoring of the glowworm larvae at 30-minute intervals has been taking place in the Glowworm Grotto since 2011. Changes in the number glowing due to noise and other disturbances from visitors detected by the monitoring were absent during the unvisited period. The influence of cave visitors on the glowworm display is the subject of a separate investigation (Merritt, in preparation).

Anthropogenic and non-anthropogenic CO₂

During a typical visited period, pCO₂ begins to rise as soon as visitors first enter the cave in the mornings and usually peaks around 11 am, clearing by about 7 pm. In the absence of visitors, the maximum daily pCO₂ was reduced, the amplitude of pCO₂ cycles was reduced and average levels were reduced, to the extent that the cave pCO₂ came close to external atmospheric levels daily. This drop to external levels only occurred when the automated door management procedure was in place, facilitating ventilation. Subsequently, when the door remained shut, the reduction in ventilation produced a pCO₂ pattern with no obvious diurnal variation. Notably it persisted at above-ambient levels, fluctuating around 500 – 600 ppm.

Another insight came from examination of pCO₂ during visits of each phase of flood events, and a sink as the flooding subsided. Dip-water from active speleothems also showed enhanced partial pressures of carbon dioxide (exceeding 5000 ppm) following periods of heavy rainfall (Miedema, 2009). The dynamics of pCO₂ in relation to storm events in caves with streams are complex, involving piston flow effects, dilution and soil CO₂ effects (Pu et al., 2014) and while the sensor network at Waitomo Glowworm Cave is not focused on stream hydrochemistry, it is now apparent that stream-water and dip-water are minor but significant contributors to the cave air pCO₂. Even in the absence of elevated stream levels or rainfall, the pCO₂ within Waitomo Glowworm Cave routinely sits above external atmospheric levels when airflow is restricted by keeping the upper door closed.

Conclusions and management implications

In heavily visited caves, knowledge of cave ventilation is important, for example, at Postojna Cave in Slovenia, chimney-effect ventilation and wind-driven ventilation both contribute to the elimination of CO₂ (Kukuljan et al., 2021a; Kukuljan et al., 2021b). In a preceding report (Hendy et al., 2022), we pointed out that Waitomo Glowworm Cave is perhaps the most intensively climate-managed tourist cave in the world, primarily due to the need to ventilate anthropogenic CO₂. Overall, the data obtained during the unvisited period provided insights into the cave microclimate that reinforce the current management practice of facilitating airflow at times of high visitor numbers and restricting it when airflow could potentially dry the internal cave surfaces, detrimentally affecting the glowworms. We conclude that the presence of visitors increases the cave temperature but the effect is short-lived due to cave ventilation. During the unvisited period, pCO₂ approached external levels when automated ventilation was in place and remained steady at about 600 ppm—well above ambient levels—when the door was closed and ventilation was restricted. Still, the above-ambient pCO₂ is low compared to the elevated pCO₂ on days when many visitors enter the cave.

It is likely that before human interventions changed the airflow dynamics of the cave, air movement, pCO₂ and cave air temperatures would have shown
variation similar to what we report here during the period when the door was sealed and no visitors were present (Pugsley, 1984). In one of the earliest reports of Waitomo Glowworm Cave microclimate a former cave manager, David R. Williams (1981) referred to climate observations from 1955 before the upper door was replaced with an iron grill: “Temperature and humidity recordings showed only slight annual variations, both showing a slight summer maximum. Diurnal variations were almost absent. Air movements through the cave were difficult to detect with a candle and no seasonal or diurnal pattern was recorded.”

The knowledge that rainfall events introduce CO$_2$ into the cave via dripwater and outgassing from the Waitomo Stream allows us to factor such conditions into identifying CO$_2$ risk days where close monitoring of visitor numbers and pCO$_2$ are required. Quantification of such sources can be incorporated into predictive microclimate models that are used to determine risk days when pCO$_2$ could exceed a threshold of 2400 ppm, specified in the cave management policy as a level at which visitation level reduction measures are put in place. On days of anticipated high visitation, a predictive model has been used to estimate pCO$_2$ based on the expected number of visitors, the predicted temperature gradient between the interior and exterior cave temperature, the cave pCO$_2$ at the start of the day and the status of the door through the day. Should the predictive model be refined, CO$_2$ outgassing sources can be taken into account in setting the maximum number of visitors per day; for example, during times of high rainfall or high stream flow.

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REFERENCES


