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# Impacts of Passage Manipulation on Cave Climate: Conservation Implications for Cave-Dwelling Bats

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## Abstract

*Human disturbance has caused declines in populations of many cave-dwelling bats and other cave-obligate organisms. Cave gating has been used to eliminate human disturbance, but few studies have assessed its impact on internal cave climate. We recorded ambient (air) and substrate (rock) temperatures at specified distances within the entrances of 3 gated and 3 open-passage caves in northeastern Oklahoma during summers 1999 and 2000 and winters 1999–2000 and 2000–2001. No differences occurred in ambient and substrate temperatures at any distance or season between gated and open-passage caves. We also monitored long-term (6 weeks) and seasonal (summer and winter) climate variables at specific distances inside 2 caves (OK-13 and OK-220) before and after modifications of their cave passages/entrances. Ambient and substrate temperatures before and after cave manipulation differed in only 1 of 12 observations in summer but in 9 of 12 observations in winter. We also monitored cave climate 7 days immediately before and after passage modification. Differences occurred at all 8 observations and at 4 of 12 observations before and after entrance and passage manipulation at OK-13 and OK-220, respectively. Airflow did not differ when monitored 7 days before and 7 days after instillation of an internal gate system in the passage of cave OK-220. Our data indicate that caves with modified entrances and passages show no changes in ambient and substrate temperatures in summer and only slight changes in winter. Although temperature changes during winter were statistically different, we posit that their biological implications on endemic cave fauna are minimal.* (WILDLIFE SOCIETY BULLETIN 34(1):137–143; 2006)

## Key words

*cave climate, cave conservation, cave gating, cave protection, gray bats,* Mytosis grisescens, *Oklahoma.*

Natural characteristics of cave entrances (number and size), physical features of cave passages (passage size, length, presence of water flow, and air flow), and surface climate (annual range of surface temperatures and barometric pressure) combine to determine internal cave climate and microclimate (McNab 1974, Tuttle and Stevenson 1978, Raesly and Gates 1987). From a biological standpoint, these factors create habitats that relate to the specialization typical of obligate cave fauna. Peck (1998) noted that ≥1,353 (425 aquatic, 928 terrestrial) animal species were restricted to subterranean habitats in the United States and Canada. In roost-restrictive, obligate cave-dwelling species such as the endangered gray bat (*Myotis grisescens*), <5% of available caves are suitable for occupation (United States Fish and Wildlife Service 1982). Microclimate of caves is most influential to bats during hibernation in winter and at maternity colonies in summer. Distribution of caves containing appropriate internal ambient conditions plays an important role in distribution and ranges of cave-dwelling bat species (Tuttle and Stevenson 1978, Raesley and Gates 1987, Thomas 1995). All North American bats that are endangered or threatened can be classified as cave-dwelling species or subspecies (McCracken 1989, Harvey et al. 1999, Pierson 1999), and 13 are obligate cave-dwellers year-round (McCracken 1989).

Human disturbance at caves has caused population declines of many cave-obligate bats (Barbour and Davis 1969, Humphrey and Kunz 1976, Tuttle 1979, American Society of Mammalogists 1992, Johnson et al. 1998, Wegiel and Wegiel 1998). As a result, cave gating has been used widely by governmental and private organizations to protect these sensitive ecosystems. Such management activities are immediate and long-term deterrents to human access at critical bat roosts and have become necessary to minimize ongoing human impacts. It is suspected that anthropogenic manipulation of cave entrances and passages to protect resident cave fauna affects internal ambient conditions primarily by altering airflow into caves passages (Humphrey 1978, United States Fish and Wildlife Service 1984, Richter et al. 1993). Various designs of gate construction and resulting effects on bat flight have been evaluated (White and Seginak 1987, Martin et al. 2003), but their effects on airflow through cave entrances, and ultimately the climate of cave interiors, have not been measured completely (Tuttle 1977, Humphrey 1978, Tuttle and Stevenson 1978, Richter et al. 1993). Appropriate experimental designs prove difficult and must take into account a myriad of inter-cave variables such as entrance size and orientation, passage length, and variable relationship between size of the entrance and the cross-section area of the cave passage. However, benefits of gating caves, while possibly altering internal ambient cave conditions, have to be weighed against persistent human entry and disturbance to critical bat roosts.

Populations of bats presently are protected with internal gate systems throughout the United States including 25 caves in northeastern Oklahoma (Martin et al. 2000). Seven of those caves have been inhabited historically by colonies of endangered gray bats (Martin et al. 2003). Fourteen entrances to caves inhabited by populations of endangered Ozark big-eared bats (*Corynorhinus townsendii ingens*), big brown bats (*Eptesicus fuscus*), eastern

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pipistrelles (*Pipistrellus subflavus*), northern long-eared bats (*Myotis septentrionalis*), and a single hibernaculum of endangered Indiana bats (*M. sodalis*) are protected similarly. Four caves that contain populations of the Ozark blind cavefish (*Amblyopsis rosae*) and Ozark blind crayfish (*Cambarus tartarus*) also are protected from human entry by internal gates. Population estimates of bats at each of these caves prior to installation of gates beginning in 1981 and post-installation estimates from 1999 and 2000 show that each cave continues to be used by stable populations of resident bats (Grigsby et al. 1993; Martin et al. 2000, 2003; Puckette 2000).

In other parts of their ranges, populations of gray bats and endangered Virginia big-eared bats (*C. t. virginianus)* do not respond favorably to gated cave passages with prolonged, stable populations like those in Oklahoma; in fact, gating cave passages is discouraged or prohibited (Pierson 1999). Nevertheless, little empirical evidence suggests that these species will not accept fully gated cave passages, and experiments elsewhere have shown that appropriately placed gates within cave passages will not impede flight (White and Seginak 1987, Martin et al. 2003). Solid obstructions to passage airflow will affect cave climate (Richter et al. 1993), but manipulations that simultaneously permit airflow and bat flight have not been thoroughly assessed. Therefore, we quantitatively compared cave climates among previously gated and nongated caves inhabited by bats in northeastern Oklahoma. Because all experimental caves were used by colonies of bats, we predicted that cave climate among gated and open-passage caves would be similar. We also evaluated 7-day, 6-week, and seasonal climates of 2 caves before and after passage manipulation and similarly predicted no effect on cave climate.

## Study Area

Our study was conducted in Adair, Cherokee, Delaware, and Ottawa counties of northeastern Oklahoma in the western limit of the Boston Mountains of the Ozark Plateau. The Plateau covers about 103,000 km$^2$ (Huffman 1959) in the central United States; elevations are 260–460 m above mean sea level. The area was dominated by outcrops of alternating layers of limestone and flint (= chert) and sandstone conducive to cave formation (Blair and Hubbell 1938). Caves in these and other similar latitudes may have served as refugia from severe post-Pleistocene winters for *C. t. ingens* and other cave-dwelling species (Humphrey and Kunz 1976). Vegetation on mountain slopes was predominantly blackjack oak (*Quercus marilandica*), post oak (*Q. stellata*), black hickory (*Carya texana*), and winged elm (*Ulmus alata*). Coralberry (*Symphoricarpos orbiculatus)* and sassafras (*Sassafras albidum*) comprised a sparse shrubby understory. Riparian areas occurred in lowlands and were dominated by silver maple (*Acer saccharinum*), river birch (*Betula nigra*), American elm (*Ulmus americana*), cottonwood (*Populus deltoides*), sycamore (*Platanus occidentalis*), and various oak species (*Quercus* spp.). Sporadic openings of managed grasslands were used for various types of agriculture (Blair and Hubbell 1938, Harvey et al. 1981).

## Methods

We compared warm season and cool season ambient and substrate temperatures between gated and open passage caves from 1999 to 2001. Those variables, and to a limited extent, airflow, also were compared before and after entrances and passages to caves OK-13 and OK-220 were manipulated in 1999–2001.

### Inter-Cave Observations

We monitored climate variables inside 6 caves in northeastern Oklahoma. Passages in 3 of the study caves were gated with internal gates intended to deter human entry. Three other study caves were open-passage caves with no anthropogenic modifications to the entrances or passages. To control factors that affected internal ambient conditions, we selected study caves that 1) had entrances oriented in an eastern or northern direction to limit solar heating of the entrance area, 2) did not have persistent stream flow that could have affected internal humidity and temperature conditions, 3) were similar in entrance size and overall passage length, and 4) exhibited similar relationships between size of the entrance and cross-section area of the cave passage.

We measured climate variables using HOBO H8 continuous data loggers (Onset Computer Corporation, Bourne, Me.). We placed 3 stations of data loggers at varying distances inside cave entrances; placement inside each cave passage coincided with historical locations of bat roost sites if such roosts were found. For statistical comparisons we grouped data logger locations into 3 intervals: <35 m, 35–60 m, and >60 m inside each cave entrance. One data logger at each station recorded ambient air temperature, relative humidity, and dew-point temperature. A second data logger recorded substrate (rock) temperature, using an external probe placed in a hole drilled 1 cm into the rock substrate. We suspended data loggers within 25 cm of the cave ceiling. If the cave ceiling could not be reached, we suspended data loggers from a rock ledge about 1.5 m from the cave floor.

We monitored climate variables during periods when mean annual surface temperatures (MAST) typically were at their highest (July–August) and lowest (December–February) levels (Richter et al. 1993). We recorded warm-season climate conditions at each cave between 12 July and 7 August 1999 and 18 July and 17 August 2000. We collected cool-season data between 15 December and 23 January 1999–2000 and 6 January and 28 February 2001. We recorded conditions every 30 minutes for 7 consecutive days at each cave (i.e., 336 observations/variable).

We used a split-split plot arrangement in a randomized complete block design to analyze data. For all analyses, we used analysis of variance procedures using PROC MIXED in PC SAS Version 8.2 (SAS Institute Inc. 1999) to compare ambient and substrate temperature means among the factors in question. To accommodate the large amount of data and to define the experimental unit, we combined observations for the 7-day period for each cave into a single mean ($n = 336$). Caves served as blocks, and season (summer and winter) was the main unit factor. The split unit factor was cave gates, and the split-split unit factor was distance inside each cave entrance where climate conditions were monitored (<35 m, 35–60 m, >65 m). In the presence of interaction between factors, we analyzed simple effects of the factors involved using a SLICE option in an LSMEANS statement. If more than one 2-way interaction was significant, we assessed the 3-way interaction. In the absence of interaction, we assessed the main effects. Statistical significance for this and all subsequent analyses was $P < 0.05$.

### Pre- and Postmanipulation

Management of 2 caves in northeastern Oklahoma provided a unique opportunity to measure internal climate variables before and after various treatments were applied to their respective entrances and passages. A summer population of about 14,000 gray bats historically has used cave OK-13 in Ottawa County, Oklahoma (Martin et al. 2000, 2003). We installed a 17-$m^2$ internal gate system 12 m within the cave passage in April 2000 to provide protection from human entry. At cave OK-220 in Adair County, Oklahoma, a <2-$m^2$ entrance had been formerly covered by a solid iron door to discourage human entry into the cave; only a 15–20-cm opening at the top of the door was available for entry by bats. The presence of a solid iron door restricted access to roost sites by bats, and airflow into and out of the cave was obstructed, resulting in a suboptimal ambient environment for bats. We removed the iron door from the cave entrance in March 2000 and installed a 1.5-$m^2$ internal gate system 7 m within the cave passage 1 year later in April 2001.

*Long-term seasonal observations.*—We measured climate variables during different seasons, as outlined above, at specific distances (20 m, 40 m, 70 m) inside cave OK-13. We recorded observations for 6 consecutive weeks each in September–October 1999 and January–March 2000 under open-passage conditions and in September–October 2000 and January–March 2001 after the internal gate was installed. We measured climate variables as outlined above but at different distances (15 m, 30 m, 70 m) inside the entrance of cave OK-220. We measured variables with the cave's airflow obstructed by the iron door for 6 consecutive weeks in September–October 1999 and March–April 2000. After the obstructive door was removed and natural airflow restored, we recorded observations again for 6 consecutive weeks in August–September 2000 and March–April 2001.

To establish units for statistical analysis, we combined observations for each of the 6-week periods into a mean of 336 observations/week for each climate variable. We used a split-plot ANOVA to compare observation means before and after manipulation of each cave's passage occurred. Main unit factors were season (summer and winter) and open/modified airflow, and the split unit factor was distance inside each cave entrance where climate was monitored.

*Short-term observations.*—We made additional observations immediately before and after each cave passage/entrance was manipulated. We recorded climate observations every 30 minutes for 7 consecutive days before and after installation of the gate system in cave OK-13 was completed. We located data loggers 20 m and 40 m inside the cave entrance but did not record ambient conditions during the period when actual construction took place. Due to a large cave passage area and associated logistical difficulties in constructing a large gate system, it took 6 weeks in March–April to install the internal gate inside cave OK-13. Therefore, monitoring of ambient and substrate temperatures before construction and immediately after completion of a gate system actually spanned 8 weeks.

We made similar observations immediately before and after the iron door was removed from the entrance at cave OK-220 in April 2000. We recorded climate observations every 30 minutes for 7 consecutive days, before and after removal of the door. Locations of data loggers within the cave passage were the same as those used during long-term observations (15 m, 30 m, 70 m). We did not record ambient conditions during the day that actual removal of the obstruction took place. One year later in April 2001, we recorded similar observations immediately before and after the 1.5-$m^2$ internal gate was installed 7 m within the passage of the cave. We also recorded airflow every 30 minutes for 7 consecutive days before and after installing the gate, using a sonic anemometer (Handar Instruments, Sunnyvale, Calif.) placed 10 m inside the cave entrance. Air moved into the cave from outside, thus flowing through the gate after its installation.

To establish units for statistical analysis, we combined observations for each cave into a mean of 48 observations/day for 7 days prior to and 7 days after manipulation of each respective passage or entrance. We used a split-plot ANOVA (SAS Institute Inc. 1999) to compare short-term observations of cave climate before and after manipulation of each cave's passage occurred. The main unit factor was open/modified airflow, and the split unit factor was distance inside each cave entrance where climate was monitored.

## Results

### Inter-Cave Observations

Following our prediction, we found no differences in ambient temperature means ($F_{1,16} = 0.02$, $P = 0.88$; Table 1) or substrate temperature means ($F_{1,16} = 0.15$, $P = 0.70$) between the 3 gated and 3 open-passage caves. No interaction occurred between cave gates and season ($F_{3,16} = 0.83$, $P = 0.49$) or cave gates and monitoring distances inside cave passages ($F_{2,32} = 0.94$, $P = 0.40$) when comparing ambient temperature means. Similarly, we found no interaction between gates and seasons ($F_{3,16} = 0.88$, $P = 0.47$) or gates and distances ($F_{2,32} = 0.76$, $P = 0.48$) when comparing substrate temperature means.

We found interactions in ambient temperatures between seasons ($F_{3,16} = 26.48$, $P < 0.0001$) and monitoring distances inside cave passages ($F_{6,32} = 4.62$, $P = 0.002$). Ambient temperatures did not

***Table 1.*** Ambient temperatures (°C) recorded in 3 caves gated with internal gates and 3 open passage caves in northeastern Oklahoma. Each value represents a mean (*n* = 336) of observations recorded every 30 minutes for 7 consecutive days in summer 1999 and 2000 and winter 1999–2000 and 2000–2001.

| CaveNo. | Gated/Open | Distance | S1999 | S2000 | W99–00 | W00–01 |
|---|---|---|---|---|---|---|
| 1 | Gated | <35m | 15.55 | 15.73 | 5.91 | 4.48 |
| | | 35–60m | 16.00 | 16.34 | 13.10 | 11.79 |
| | | >60m | 14.56 | 14.78 | 13.81 | 12.99 |
| 2 | Gated | <35m | 13.99 | 14.00 | 11.26 | 9.45 |
| | | 35–60m | 13.83 | 14.03 | 9.81 | 11.23 |
| | | >60m | 13.77 | 13.98 | 14.35 | 13.33 |
| 3 | Gated | <35m | 14.00 | 14.51 | 11.66 | 10.31 |
| | | 35–60m | 13.90 | 14.49 | 12.30 | 10.80 |
| | | >60m | 13.69 | 14.04 | 12.99 | 11.86 |
| 4 | Open | <35m | 14.59 | 15.10 | 10.98 | 8.88 |
| | | 35–60m | 14.93 | 15.55 | 11.73 | 9.83 |
| | | >60m | 14.22 | 14.89 | 13.45 | 12.22 |
| 5 | Open | <35m | 12.59 | 13.19 | 11.42 | 9.73 |
| | | 35–60m | 12.44 | 12.79 | 11.92 | 10.35 |
| | | >60m | 13.47 | 13.86 | 12.81 | 11.30 |
| 6 | Open | <35m | 17.23 | 14.07 | 13.38 | 5.80 |
| | | 35–60m | 14.58 | 13.66 | 13.62 | 9.75 |
| | | >60m | 15.36 | 14.12 | 13.90 | 12.91 |

differ at any distance among the 6 caves during summer 1999 ($F_{2,32} = 0.22$, $P = 0.81$) and 2000 ($F_{2,32} = 0.04$, $P = 0.96$). Ambient temperatures differed relative to distance among the 6 caves in winter 1999–2000 ($F_{2,32} = 6.54$, $P = 0.0042$) and 2000–2001 ($F_{2,32} = 15.93$, $P < 0.0001$). Statistical results for substrate temperatures correlated closely with those of ambient temperatures depicted in Table 1 and subsequent figures.

### *Pre- and Postmanipulation*

*Long-term seasonal observations.*—We found interactions between season (summer and winter) and open/manipulated passage for both ambient (Figure 1) and substrate temperatures at cave OK-13. Mean ambient temperatures did not differ under either airflow treatment (gated vs. open passage) at any distance (20 m: $F_{1,59.5} = 0.99$, $P = 0.33$; 40 m: $F_{1,59.5} = 0.38$, $P = 0.53$; 70 m: $F_{1,59.5} = 1.95$, $P = 0.16$) during warm-season observations between September–October (1999–natural, 2000–gated). However, we found that mean substrate temperatures were cooler after passage manipulation at a distance of 20 m ($F_{1,59.5} = 5.37$, $P = 0.02$) but not at 40 m ($F_{1,59.5} < 0.01$, $P = 0.99$) or 70 m ($F_{1,59.5} = 1.37$, $P = 0.25$).

Mean ambient temperatures at OK-13 in winter were warmer under natural airflow conditions (January–March 2000) than under gated airflow (January–March 2001) and differed at all 3 locations (20 m: $F_{1,59.5} = 4.89$, $P = 0.03$; 40 m: $F_{1,59.5} = 6.43$, $P = 0.01$; 70 m: $F_{1,59.5} = 4.47$, $P = 0.04$). Substrate temperature means were cooler at 20 m ($F_{1,59.5} = 4.86$, $P = 0.03$) and 40 m ($F_{1,59.5} = 6.25$, $P = 0.02$) but not significant at 70 m ($F_{1,59.5} = 3.16$, $P = 0.08$).

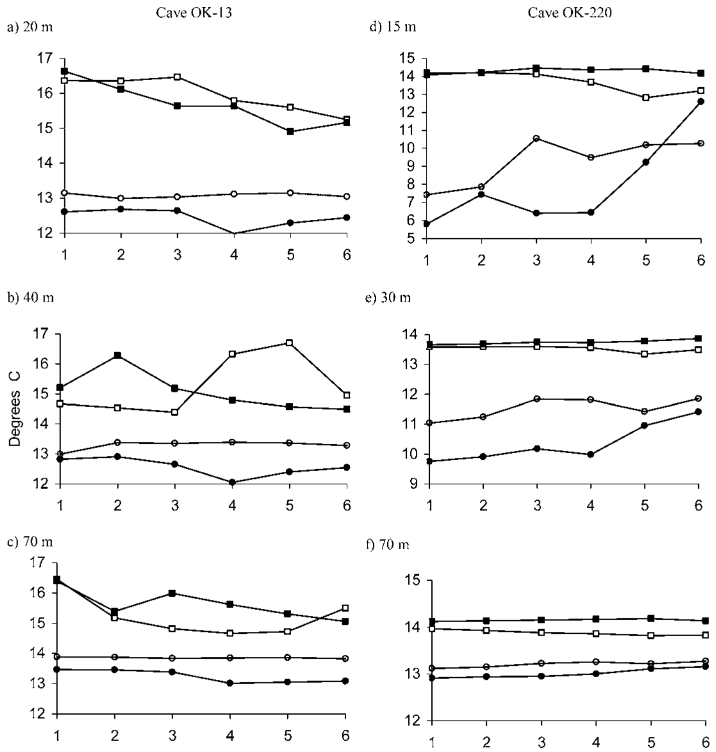

***Figure 1.*** Ambient temperatures at 3 distances from the cave entrance recorded for 6 consecutive weeks in cave OK-13, Ottawa County, Oklahoma (a, b, and c) in summer 1999 (□) and winter 2000 (○) during conditions of natural airflow into the cave, and in summer 2000 (■) and winter 2001 (●) after an internal gate system was installed 12 m inside the cave passage. Ambient temperature means from cave OK-220 (d, e, and f) in summer 1999 (□) and winter 2000 (○) while natural airflow into the cave was obstructed by a solid iron door, and subsequent observations recorded in summer 2000 (■) and winter 2001 (●) after the door was removed and natural airflow restored. Each data point represents mean observations ($n = 336$) recorded every 30 minutes over a 7-day period.

At cave OK-220, where an iron door covered the entrance, we found interactions between season (summer and winter) and open/manipulated passage and between season and distance. No differences occurred in mean ambient temperatures (Figure 1) at any distance (15 m: $F_{1,52.5} = 1.29$, $P = 0.26$; 30 m: $F_{1,52.5} = 0.18$, $P = 0.67$; 70 m: $F_{1,52.5} = 0.28$, $P = 0.60$) during warm-season observations in September–October 1999 when airflow was obstructed and August–September 2000 when the passage was unobstructed. Within the same warm-season observations, we found no differences in mean substrate temperatures at any distance inside the cave passage (15 m: $F_{1,51.1} = 1.09$, $P = 0.30$, 30 m: $F_{1,51.1} = 0.10$, $P = 0.75$, 70 m: $F_{1,51.1} = 0.18$, $P = 0.67$).

Mean ambient temperatures at cave OK-220 during winter–early spring between obstructed airflow (February–April 2000) and unobstructed airflow (February–April 2001) were cooler after removing the iron door and differed at 15 m ($F_{1,52.5} = 6.70$, $P = 0.01$) and 30 m ($F_{1,52.5} = 5.32$, $P = 0.03$), but not at 70 m ($F_{1,52.5} = 0.15$, $P = 0.70$; Figure 1). Similarly, mean substrate temperatures during those same comparisons were cooler after restoring natural airflow and differed at 15 m ($F_{1,51.1} = 18.07$, $P < 0.0001$) and 30 m ($F_{1,51.1} = 7.19$, $P = 0.01$), but not at 70 m ($F_{1,51.1} = 0.19$, $P = 0.66$).

*Short-term observations.*—We noted interaction between gated/open-passage conditions and distances inside the cave entrance at cave OK-13. Mean ambient temperatures recorded 7 days before and 7 days after installation of an internal gate system differed at distances of 20 m ($F_{1,21.1} = 36.02$, $P < 0.0001$) and 40 m ($F_{1,21.1} = 5.17$, $P = 0.03$; Figure 2). Similarly, we found differences in mean substrate temperatures at 20 m ($F_{1,21.1} = 20.04$, $P < 0.0001$) and 40 m ($F_{1,21.1} = 20.40$, $P < 0.0001$). Mean ambient and substrate temperatures were warmer after installation of the gate system at each distance.

Similarly, we found interactions (open/obstructed airflow and distance) when comparing mean temperatures 7 days before and 7 days after the iron door was removed from OK-220's entrance in April 2000 (Figure 3*a*). Temperature means were warmer after the door was removed and differed at 15 m for ambient ($F_{1,32.9} =$

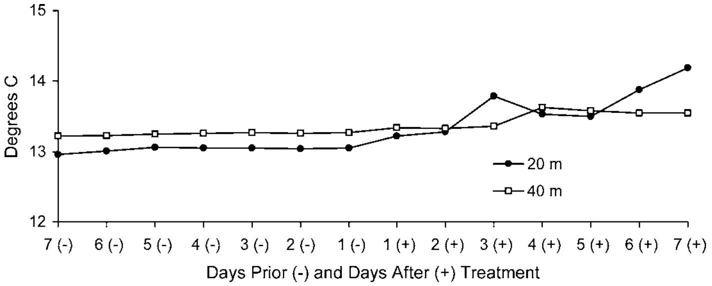

***Figure 2.*** Ambient temperatures at 20 and 40 m from the cave entrance in cave OK-13 in Ottawa County, Oklahoma. Observations were made 7 days before (–) and 7 days after (+) an internal gating system was installed 12 m inside the cave entrance in March–April 2000. Each data point represents mean observations ($n = 48$) recorded every 30 minutes for a 24-hour period.

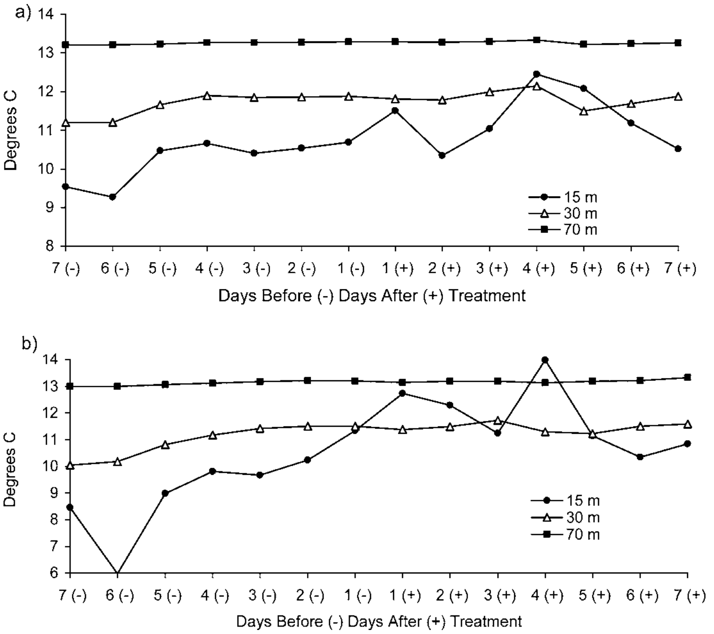

***Figure 3.*** Ambient temperatures at 3 distances from the cave entrance in cave OK-220 in Adair County, Oklahoma. Observations were made in April 2000 7 days before (–) and 7 days after (+) an iron door covering the cave entrance was removed allowing natural airflow to resume (a), and 7 days before (–) and 7 days after (+) an internal gate system was installed 7 m inside the cave entrance in April 2001 (b). Each data point represents a mean of 48 observations recorded every 30 minutes for a 24-hour period.

22.87, $P < 0.0001$) and substrate temperatures ($F_{1,32.9} = 49.61$, $P < 0.0001$). No differences existed in ambient temperatures at 30 m ($F_{1,32.9} = 0.62$, $P = 0.44$) or 70 m ($F_{1,32.9} = 0.01$, $P = 0.92$) or substrate temperatures at 30 m ($F_{1,32.9} = 3.21$, $P = 0.08$) and 70 m ($F_{1,32.9} = 0.06$, $P = 0.81$).

We found similar results when comparing ambient and substrate temperatures recorded 7 days before and 7 days after installation of an internal gate system in the cave passage 1 year later in April 2001 (Figure 3*b*). Mean temperatures were warmer after the gate was installed at 15 m for ambient ($F_{1,33.6} = 28.60$, $P < 0.0001$) and substrate temperatures ($F_{1,31.2} = 47.11$, $P < 0.0001$). No differences existed in ambient temperatures at 30 m ($F_{1,33.6} = 1.12$, $P = 0.30$) or 70 m ($F_{1,33.6} = 0.03$, $P = 0.86$) or substrate temperatures at 30 m ($F_{31.2} = 3.35$, $P = 0.08$) and 70 m ($F_{1,31.2} = 0.08$, $P = 0.79$).

We recorded airflow direction through the internal gate system at 30-minute intervals to ensure that it was flowing into the cave from outside. Airflow recorded at cave OK-220 did not differ when recorded 7 consecutive days during natural, unobstructed conditions and 7 consecutive days after an internal gate system was installed in the passage in April 2001 ($F_{1,11} = 0.01$, $P = 0.94$; Figure 4).

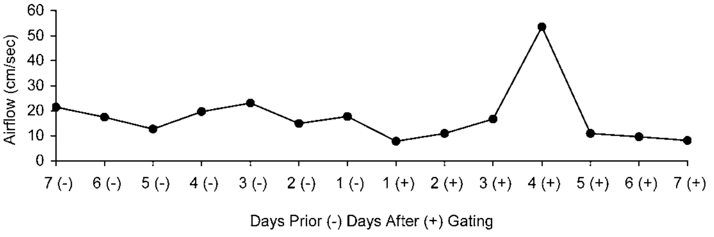

***Figure 4.*** Airflow at cave OK-220 in Adair County, Oklahoma. Observations were made 7 days before and 7 days after an internal gate system was installed 7 m inside the cave entrance in April 2001. Each data point represents a mean of 48 observations recorded every 30 minutes for a 24-hour period.

## Discussion

### *Factors Affecting Cave Climate*

In obligate cave-dwelling species of bats, microclimate variables are most influential during hibernation and in summer maternity colonies. In hibernacula, ambient and substrate temperatures influence body temperature and ultimately metabolic rates of hibernating bats (McNab 1974, Humphrey 1978). In summer maternity roosts, fetal and neonatal growth rates are affected directly by suboptimal body temperatures of pregnant females and juveniles, and thermoregulatory stress in these bats may result in slow maturation, thus reducing survival and natality (Studier and O'Farrell 1972, Humphrey 1975).

Recent studies have shown that relative to flight, populations of cave-dwelling bats are not adversely affected by appropriately placed gates in twilight or "dark zones" within cave passages, which are intended to restrict human access to bat roosts and colonies (White and Seginak 1987; Martin et al. 2000, 2003). However, data on effects of modifications of cave entrances, such as internal cave gates to internal cave microclimates, are extremely limited (Richter et al. 1993). Physical characteristics that affect cave climate include passage size, entrance size, entrance orientation (vertical vs. horizontal), number of entrances, passage to entrance elevational configurations, and presence of water flow (Tuttle and Stevenson 1978, Raesly and Gates 1987). Effects that external climate such as annual range of surface temperatures, atmospheric pressure, and airflow have on internal ambient cave environments also are well documented (Tuttle and Stevenson 1978, Richter et al. 1993). Although influenced directly by changes in temperature and atmospheric pressure, airflow may be most influential in dictating climate inside caves. Caves in our study tended to breath "outwardly" in summer because internal air was cooler than outside air and outside air was warmer than MAST. We noted minimal differences in internal ambient and substrate temperatures in summer compared with winter when caves breathed "inwardly" because external air was cooler than internal air temperatures and cooler than MAST.

### *Pre- and Postmanipulation*

Although statistical differences in ambient and substrate temperatures were common in winter before and after passage/entrance manipulation, they do not seem particularly important relative to cave climate or bat biology. When we collected long-term observations, the lowest mean minimum winter ambient temperature at any distance during a 6-week period of observations before cave OK-13 was gated in 2000 (12.99°C) and after gating in 2001 (11.99°C) differed by only 1°C. The highest maximum mean ambient temperature at any distance during the same 6 weeks before (13.86 °C in 2000) and after gating (13.47 °C in 2001) of cave OK-13 differed by only 0.39°C. Similar differences occurred at cave OK-220, where extremes in minimum winter ambient temperatures at any distance during a 6-week period of observations before removing the iron door in 1999 and during normal airflow in 2000 differed by only 1.63°C. Extremes in maximum ambient temperatures at any distance before and after the obstruction was removed differed by only 0.11°C.

When observing short-term affects of passage manipulation on cave climate at cave OK-13, we noted differences between extreme minimum (1.23°C) and maximum (0.41°C) mean ambient temperatures at either distance during the entire monitoring period were small, as were differences between extreme minimum (1.10°C) and maximum (0.47°C) mean substrate temperatures. At cave OK-220, manipulating the entrance and passage did not immediately affect mean temperature variables at distances $>15$ m, or airflow $<3$ m from the internally placed gate. Differences in mean ambient and substrate temperatures $<15$ m inside the cave entrance were indicative of variable climatic conditions that persist at this distance inside most cave passages.

Our data indicate ranges of winter air temperatures in caves (Table 1: 4.48–14.35 °C) corresponded closely with those observed at hibernating clusters of Ozark big-eared bats in Oklahoma (5.5–11.2 °C; Clark et al. 1996) and Arkansas ($<12$ °C; Harvey and Barclay 1990). Studies involving gray bats noted temperature ranges of 3.3 °C (Tuttle 1976) and 5 °C (United States Fish and Wildlife Service 1982) at respective hibernacula. Except on rare occasions, colonial gray bats were historically absent from all caves in northeastern Oklahoma during hibernation, and observations of hibernating populations of Ozark big-eared bats in caves with internal gate systems indicated stable numbers (Puckette 2000). While it is possible that passage manipulation, as we conducted it, could push site-specific temperatures beyond such a range by a degree or so, we believe it is unlikely to alter the entire cave landscape in such a way as to cause abandonment, which is often a byproduct of human intrusion.

## Management Implications

Humphrey (1978) and Richter et al. (1993) reported harmful effects of warm ambient and substrate temperatures at roosts of hibernating Indiana bats. Each instance resulted from anthropogenic modifications at cave entrances, specifically solid walls that impeded air exchange. In our study, modified passages following accepted cave-gating protocols (White and Seginak 1987; Martin et al. 2000, 2003) and exhibiting moderate to low volumes of airflow ($<30$ cm/sec) showed no changes in ambient and substrate temperature means when airflow moved outward in summer and only slight changes in winter. Seasonal variations in surface climate, entrance characteristics (Tuttle and Stevenson 1978), and physical structure of the cave (Twente 1955, Raesly and Gates 1987) probably had a greater impact on climate of cave interiors than our manipulations of the cave passage or entrance.

Minimal effects of appropriately manipulated passages and entrances are further substantiated by the presence of stable populations of gray bats and Ozark big-eared bats in such caves in Oklahoma (Grigsby et al. 1993; Puckette 2000; Martin et al. 2000, 2003). Our results suggest that inferences that cave gates alter airflow in cave passages (Humphrey 1978, United States Fish and Wildlife Service 1984, Richter et al. 1993), and ultimately affect ambient temperature, humidity, and substrate temperature inside caves, appear to be empirically unfounded. We recommend that internal gates be placed within "dark zones" of cave passages allowing persistent airflow, as opposed to those that cover cave entrances externally. This tactic is particularly important when casual or persistent human disturbance is of primary concern at critical bat roosts.

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