EFFECTS OF PASSAGE MANIPULATION ON CAVE CLIMATE AND BAT BEHAVIOR: MANAGEMENT IMPLICATIONS FOR CAVE-DWELLING BATS

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CHAPTER I

CLIMATE AND EXIT BEHAVIOR OF BATS FROM GATED AND OPEN-PASSAGE CAVES

Abstract

Persistent or casual human disturbance incurred by bats in maternity caves and hibernacula has been implicated as a major cause for the decline in populations of most cave-dwelling bats. Efforts intended to eliminate disturbance resulting from human entry to these caves typically are accomplished by construction of gates at cave entrances. In northeastern Oklahoma, 24 entrances to caves inhabited by two endangered bat species and one subspecies presently are protected from human entry with internal "dark-zone" gates. Effects of internal cave gates on resident bats and microclimate of cave interiors have not been measured completely. Cave gates may alter airflow in cave passages, which may affect ambient temperature, humidity, and substrate temperature. Such alterations in ambient conditions ultimately may affect life-history characteristics of bats such as body temperature, metabolic rates, fetal and neonatal development, and thermoregulation. Cave gates also may impede movements of large colonies of bats from roost caves, which may increase swarming and increase predation, or result in young being dropped and abandoned. In this study, ambient (air) and substrate (rock) temperatures and their respective ranges were recorded at six caves in northeastern Oklahoma during summers 1999 and 2000 and winters 1999-2000 and 2000-2001. Observations were collected at specified distances (<35 m, 35-60 m, >60 m) within the entrances of three gated and three open-passage caves. No differences occurred in ambient and substrate temperatures at any distance or season between gated and open-passage caves during summer. Ambient and substrate temperature ranges differed at distances close to the cave entrances only in winter 1999-2000, but not during summers or winter 2000-2001. Initiation of flight emergence at three gated and three open-passage caves were recorded at caves inhabited by colonies of gray bats in June and July 1999 and 2000 to assess effects of cave gates on bat flight. No differences in timing of initiation of exit flights were found between colonies from gated versus open-passage caves.

Introduction

About 18 of the 45 species of bats found in North America rely substantially on caves throughout the year, and 13 use caves year-round (McCracken 1989). These caves are used as winter hibernacula, stopover roost sites during migration, summer roost sites, or maternity sites where adult females give birth to their young. All North American bats listed as endangered or threatened by the U.S. Fish and Wildlife Service are cave-dwelling species or subspecies (McCracken 1989; Harvey et al. 1999; Pierson 1999). Persistent or casual human disturbance at maternity caves and hibernacula has been implicated as a major cause for the decline in population of most cave-dwelling bats (Barbour and Davis 1969; Humphrey and Kunz 1976; Tuttle 1979; American Society Mammalogists 1992). Endangered or threatened populations cannot be viable with elevated mortality rates or poor recruitment as a result of disturbance (McCracken 1989; American Society of Mammalogists 1992).

Conservation efforts concentrating on protecting these caves and the colonies of bats that they harbor are possibly the most important contemporary issues in bat conservation in the United States (American Society of Mammalogists 1992). These efforts usually are intended to eliminate disturbance resulting from human entry to these caves. Protection typically is accomplished by constructing gates at cave entrances, fencing cave entrances, placing warning signs at entrances, and maintaining a close and positive rapport with private landowners. Protection of populations of cave-dwelling bat populations by placing gates in entrances of caves can be an effective, immediate, and long-term method to deter human access to critical bat roosts (Humphrey 1978; Tuttle 1977; Tuttle and Stevenson 1977). Tuttle and Stevenson (1977) discussed important effects of cave structure and elevational displacement of internal air volume on ambient cave conditions. From a biological standpoint, these factors combine to create habitats that correlate with high evolutionary specialization typically exhibited by obligate cave fauna. Peck (1998) noted $\geq$ 1,353 (425 aquatic, 928 terrestrial) animal species that were restricted to subterranean habitats in the U.S. and Canada. In roost restrictive, obligate cave-dwelling species such as the gray bat (*Myotis grisescens*), <5% of available caves are suitable for occupation (U.S. Fish and Wildlife 1982). In obligate cave-dwelling species of bats, microclimate variables are most influential during hibernation and at maternity colonies in summer. It is evident that distribution of caves containing appropriate internal ambient conditions plays an important role in distribution and ranges of cave-dwelling bat species (Tutttle and Stevenson 1977; Raesley and Gates 1987; Thomas 1995).

History of Cave Gating in Oklahoma

Construction of restrictive structures at cave entrances has evolved considerably over the past 25 years. Original designs were constructed in cage-like fashion exterior to the cave entrance. This placement resulted in some caves being abandoned by resident bats (Tuttle 1977; 1979; Clark et al. 1996). In Delaware County, Oklahoma, such a gate placed over a cave entrance in 1971 resulted in eventual abandonment of the cave by a maternity colony of gray bats by 1981. An internal gate was placed 15 m inside the cave passage, and the older external cage (installed in 1971) was reconstructed to be left open during periods of bat use. A maternity colony of gray bats used the cave during maternity seasons in 1998, 1999, and 2001. Estimates of colony size were 25,000 bats in 1998, 27,000 in 1999 (Martin et al. 2000), and 23,000 in 2001.

In 1980 and 1982, two additional caves inhabited by maternity colonies of gray bats in Adair and Delaware counties, Oklahoma, were gated. The exterior features of those cave entrances, however, caused gates to be placed within dark zones of the cave passages 9 –15 m, inside entrances. Each cave continues to be used by maternity populations of about 5,400 and 14,000 gray bats (Martin et al. 2000). These were the first instances of cave-dwelling populations of bats protected by an “interior” gate system in the United States. A third gray bat maternity colony in Cherokee County, Oklahoma, was gated with similar results by using the same type of placement in 1991 (Grigsby et al. 1993).

Although general designs of gate construction continue to evolve, placement of gates within dark zones of cave passages, such as those in northeastern Oklahoma, is now an accepted protocol for cave gating throughout the United States (White and Seginak 1987).

Populations of bats are presently protected with internal gate systems at 24 entrances to caves in northeastern Oklahoma. Seven of those caves have been inhabited historically by colonies of gray bats. Thirteen entrances to caves inhabited by populations of Ozark big-eared bats (*Corynorhinus townsendii ingens*), big brown bats (*Eptesicus fuscus*), eastern pipistrelles (*Pipistrellus subflavus*), northern bats (*Myotis septentrionalis*), and a single hibernaculum of Indiana bats (*Myotis sodalis*) are protected similarly. Four caves that contain populations of the Ozark blind cavefish (*Amblyopsis rosae*) and Ozark blind crayfish (*Cambarus* sp.) also are protected from human entry by internal gates.

Three cave-dwelling species of bats found in northeastern Oklahoma have been federally listed by the U.S. Fish and Wildlife Service: Ozark big-eared bat, gray bat, and Indiana bat. Populations of these bats that are protected with internal gates are located in Adair, Delaware, Cherokee, Leflore, and Ottawa counties of Oklahoma. Population estimates of bats at each of these caves prior to installation of gates in 1981 and post-installation estimates from 1999 suggest that each cave continues to be used by resident bat populations (Martin et al. 2000).

Each of the 24 entrances to caves that have been gated in Oklahoma have unique physical characteristics of passage size, location of the nearest bat roost to the entrance, and number of entrances used by bats. Internal gates are placed such as to protect the nearest historical roost area to the cave entrance. Gate distances from cave entrances are 3-17 m. Passage areas where gates are located are 1.4 – 15 m^2.

Internal gate construction has been of horizontal angle-iron bars since the mid-1980's. This material and design seem to maximize protection from human entry, have nominal effects on airflow, and present limited obstruction to bat flight (White and Seginak 1987). With the exception of a single cave that was gated before angle-iron gates became popular, all gates in Oklahoma caves are of the angle-iron design.

Although placement of gates within "dark zones" of cave passages may be the most effective method to deter human access to critical bat roosts, their effects on resident bats and microclimate of cave interiors have not been measured completely (Tuttle 1977; Tuttle and Stevenson 1977; Humphrey 1978; Richter et al. 1993). Various designs of gate construction and resulting effects on bat flight have been tested (White and Seginak 1987; Ludlow and Gore 2000), but effects that gates have on the microclimate of cave interiors have not. Experimental designs must take into account a myriad of inter-cave variables such as entrance size and orientation, passage length, and entrance to passage ratio in surface area.

Because of the possibility of colony abandonment as a result of cave gates, most investigators encourage caution when placing internal gates in cave passages to protect obligate cave-dwelling bat species (Pierson 1999; Ludlow and Gore 2000). Apprehension toward gating is especially high over use of full-passage gates and gating more than a single entrance. An often-used management approach in some areas of the gray bat's range involves gate construction that leaves the upper part of the passage open. This area of the passage is typically where the majority of bat flight occurs. Although this design may be less obstructive to bat flights, it does not afford the same protection from human disturbance to the colony that a full passage gate does. In contrast, all internal gates in Oklahoma caves completely fill cave passages. Furthermore, two gray bat caves that are gated in Oklahoma have two entrances each that are used during entrance and exit by bats. In those particular caves, both entrances are protected with complete gates, and estimates continue to indicate stable populations (Martin et al. 2000).

Caves in Oklahoma that have internally gated passages exhibit rather common or typical characteristics. Relatively small colony sizes (<30,000) of resident bat populations, relatively small gated passages conducive to lower volumes of airflow, and internal positioning of gate structures in "dark zones" of cave passages probably contribute to the apparent acceptance of full passage gates by resident bat populations in eastern Oklahoma. Acceptance is further substantiated by extant bat colonies that use caves in eastern Oklahoma with manipulated passages and entrances exhibiting stable populations (Martin et al 2000; Puckette 2000).

The intent of this study was to compare abiotic (ambient temperature, substrate temperature, relative humidity, and dew point) and biotic (initiation of exit flights) characteristics between gated and nongated caves that are inhabited by bats in eastern Oklahoma. In light of the present use of gated caves by colonies of bats with stable populations in Oklahoma, I predicted that impacts on the microclimate of the cave interiors and bat behavior by the installation of these systems would be minimal.

Materials and Methods

Internal Ambient Climate

Four climate variables (ambient temperature, substrate temperature, relative humidity, and dew point) were monitored inside six caves in northeastern Oklahoma. Three 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.

Climate variables were measured using HOBO H8 continuous data loggers (Onset Computer Corporation, Bourne, Maine). Three stations of data loggers were placed 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, data logger locations were grouped into three intervals: <35 m, 35-60 m, and >60 m. One data logger at each station collected ambient air temperature, relative humidity, and dew-point temperature. A second data logger monitored substrate temperature using an external probe placed in a hole drilled 1 cm into the rock substrate. Data loggers were attached together and suspended within 25 cm of the cave ceiling. If the cave ceiling could not be reached, data loggers were suspended from a rock ledge about 1.5 m from the cave floor.

Climatic variables were monitored during periods when mean annual surface temperatures (MAST) were typically at their highest (July-August) and lowest (December-February) levels (Richter et al. 1993). Warm-season climatic conditions were recorded at each cave between 12 July and 7 August 1999 and 18 July and 17 August 2000. Cool-season data were collected between 15 December and 23 January 1999-2000 and 6 January and 28 February 2001. Conditions were recorded every 30 minutes for 7 consecutive days at each cave for a total of 336 observations/variable. Difficulty in recording relative humidity occurred when logger sensors became saturated in the high-humidity cave environments. When that occurred, readings exceeded 100% and were considered inaccurate by the manufacturer. When recorded dew-point observations were lower than ambient temperatures, they were used to calculate relative humidity. A combination of actual relative humidity recordings and those that were obtained by using dew-point and ambient air temperatures resulted in only a scattered representation of ambient cave humidity. Although useful for anecdotal inferences, they were not suitable for statistical comparisons.

To control factors that affected internal ambient conditions, I 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, and 3) were similar in entrance size, overall passage length, and entrance to passage ratios in surface area.

A split-split plot in a randomized complete-block ANOVA (SAS Institute Inc. 1999) compared ambient and substrate temperature means between gated and open passage caves. Observations for the 7-day period for each cave were combined into a single mean (n = 336). Caves were blocked 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). As a measure of variance, a temperature range for each mean was determined and compared between gated and open-passage caves using the same randomized complete-block ANOVA. Statistical significance was determined at $P < 0.5$.

Colony Exit Behavior

Initiation of flight emergences at three gated and three open-passage caves was recorded at caves inhabited by colonies of gray bats in June and July 1999 and 2000. Flight emergence times were observed using an infrared light source and night-vision optics. This nonintrusive method produces minimal disturbance to exiting colonies while observing emergence initiation times, emergence duration, and even population estimates of relatively small colonies (U.S. Fish and Wildlife Service 1995). Swarming and circling by bats at a cave entrance as twilight approaches are typical and may allow bats to sample light conditions outside the cave (Twente 1955; Clark 1991). During this study, it was not unusual to observe 25-30 gray bats swarming (exiting and re-entering) in the entrance for 5-10 minutes before they actually began to exit the cave without re-entry. Exiting bats were counted continuously in 60-second increments. Emergence times were recorded when >30 gray bats exited a cave entrance without re-entry within a 60-second time period. That method was continued and a subsequent emergence time was recorded when >60 gray bats exited without re-entry within a 60-second interval.

Three exit observations were made at each of the six caves in 1999 and 2000 (n = 36). To remove effects of variations in light intensity attributable to changes in sunset times over a five-week period, each recorded time was converted to minutes after official sunset. Official sunset times were derived from the nearest U.S. Naval Observation Station to each study cave. Range of distances between each cave and its nearest observation station was 8-15 km. Exit observations not conducted when there was a threat of rainfall. Extrinsic factors thought to effect emergence times such as cloud cover, extended twilight hours in summer months, and whether or not a colony was a maternity colony were not considered (Clark 1991; McAney and Fairley 1988).

A randomized complete block ANOVA (SAS Institute Inc. 1999) compared timing of flight exits of gray bats between gated and open passage caves. Each year (1999 and 2000) was blocked, and individual caves were subsample experimental units. I hypothesized exit flights would be delayed and slowed if flight was impeded, or an increase in swarming would be induced by the presence of a gated passage.

Results

Internal Ambient Climate

No differences occurred in ambient temperature means (Table 1) between gated and open-passage caves (F = 0.02, df = 1,16; P = 0.88; Fig. 1). No interaction occurred between cave gates and seasons (F = 0.83, df = 3,16; P = 0.49) or cave gates and distances (F = 0.94, df = 2,32; P = 0.40). Similar results were obtained comparing mean substrate temperatures (Table 2) between gated and open-passage caves (F = 0.15, df = 1,16; P = 0.70;Fig. 2), with no interaction between gates and seasons (F = 0.88, df = 3,16; P = 0.47) or gates and distances (F = 0.76, df = 2,32; P = 0.48). There were significant effects of season (F = 26.48, df = 3,16; P = <.0001) and distances (F = 8.86, df = 2,32; P = 0.0009) inside cave entrances where temperatures were monitored.

I used temperature ranges as a measure of variance. Maximum temperature ranges at gated caves were 1.48°C in summer and 6.65°C in winter. Corresponding maximum temperature ranges in open-passage caves were 2.48°C in summer and 3.18°C in winter. No effect of gates occurred in ambient temperature ranges (F = 1.57, df = 1,4; P = 0.28), but interaction did occur between gated passages and seasons (F = 5.96, df = 3,48; P = 0.0017). Ranges differed between gated and open-passage caves only in winter 1999-2000 at distances <35 m (F = 12.66, df = 1,48; P = 0.0009) and 35-60 m (F = 6.66, df = 1,48; P = 0.01).

A gate effect (F = 5.01, df = 1,48; P = 0.03) and interaction between gates and season (F = 7.13, df = 3,48; P = 0.0005) occurred when comparing substrate temperature ranges. Substrate temperature ranges differed between gated and open-passage caves only in winter 1999-2000 at distances <35 m (F = 25.56, df = 1,48; P = <0.0001) and 35-60 m (F = 9.72, df = 1,48; P = 0.0031).

Colony Exit Behavior

Mean exit times (Table 3) adjusted to minutes after official sunset did not differ between cave types when initiation of a colony exit was determined by >30 bats/60 seconds (F = <0.01, df = 1,4; P = 0.979;Fig. 3) or >60 bats/60 seconds (F = 0.02, df = 1,4; P = 0.902). Anecdotal observations did not reveal a relative increase in swarming at gated caves as is typical when colonies begin exiting from a cave, or dropping of any young at or near cave entrances.

Discussion

Effects of temperature, atmospheric pressure, and airflow on internal ambient cave environments are well documented (Tuttle and Stevenson 1977; Richter et al 1993). Airflow is influenced directly by changes in temperature and atmospheric pressure and may be the most influential factor in dictating ambient conditions inside of caves.

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. Poor thermoregulation in these bats may result in slow maturation, thus reducing survival and natality (Studier and O'Farrell 1972; Humphrey 1975).

Natural characteristics of cave entrances affect internal ambient conditions, including number of entrances, size of entrances, passage size, presence of water flow, air flow, and annual range of temperatures outside the cave (Tuttle and Stevenson 1977). It is suspected also that cave gates can alter airflow in cave passages (Humphrey 1978; Richter et al. 1993; U.S. Fish and Wildlife Service 1984). Designed experiments and quantitative data on effects of modifications to cave entrances on internal cave microclimates, such as cave gates, are limited to nonexistent (Richter et al. 1993). Surface and entrance characteristics between caves are highly variable and control of this variation to establish a sound experimental design can be difficult.

It also is feared that cave gates can interrupt or impede exit of large colonies of bats from roost caves. An increase in swarming activity before exiting or entering a cave that is gated may increase risk of predation or result in young being dropped and abandoned (Tuttle 1977; 1979; White and Seginak 1987; Ludlow and Gore 2000).

Internal Ambient Climate

A degree of inherent variability was expected among the six caves, each with distinct entrances, passage sizes, passage lengths, and a multitude of other physical, climatic, and abiotic factors contributing to unique endemic environments. These factors contribute to the significant effects of season and monitoring distances inside cave passages. It is intriguing, however, that no significant differences of internal ambient and substrate temperature means or ranges occurred between gated and open-passage caves. Study caves selected for this experiment have a tendency to breath "outwardly" in summer when internal air is cooler than outside air and outside air is warmer than the mean annual surface temperatures (MAST). If airflow typically moves out of cave entrances during these warm months and gate locations are generally < 15 m of most entrances, it can be predicted that there will be minimal effects on internal ambient and substrate temperatures.

These caves tend to breath "inwardly" in winter when external air is cooler than internal air temperatures and cooler than MAST. If airflow were impeded in any manner by internally placed gates, it would be magnified in these months when external airflow is carried into the cave's interior. Seasonal differences in ambient and substrate temperatures occurred among all caves in winter at <35 m and 35-60 m, but not at locations considered deep in cave passages at >60 m. No such differences occurred among all caves during summer monitoring periods.

These seasonal effects among all caves in winter probably contributed to significant differences in ranges of ambient and substrate temperatures in winter 1999-2000. Ranges of cool-season air temperatures in these caves (4.48-14.51°C) correspond closely with those observed at hibernating clusters of Ozark big-eared bats in Oklahoma (5.5-11.2°C; Clark et al. 1996) and in Arkansas (<12°C; Harvey and Barclay 1990), and those indicated for gray bats (6-11°C; U.S. Fish and Wildlife Service 1982). Except on rare occasions, colonial gray bats are historically absent from all caves in northeastern Oklahoma during hibernation. Observations of hibernating populations of Ozark big-eared bats in caves with internal gate systems indicate stable numbers (Puckette 2000).

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. It is apparent from these data, however, that internally gated caves exhibiting what might be considered moderate to low volumes of airflow do not differ in ambient and substrate temperatures from open-passage caves. It may be correct to assume, therefore, that appropriately placed internal gate systems that allow ample airflow would have minimal effects on internal ambient cave conditions and life histories of bats.

Colony Exit Behavior

Many factors can delay a colony's exit or promote an early emergence from a cave entrance. Maternity colonies have been noted to emerge later, relative to sunset, during lactation (Clark 1991; Kunz 1974; McAney and Fairley 1988), and delayed emergence also may be a result of longer twilight hours in summer (McAney and Fairley 1988). In my study, all observations were made at maternity colonies of gray bats, except cave number 5 (Fig. 5) that contains a bachelor colony during the maternity season. It seems apparent, however, that emergence is most dependent on light intensity (Kunz 1974; Prakish 1962; Stebbings 1968).

The effect that an internal gate has on delaying departure from a cave has not been tested although White and Seginak (1987) tested effects of three gate designs on affinity of bat flight through a particular design. Speculation persists among cave biologists that placing gates in cave passages precipitates an increase in swarming by bats as they emerge from a cave, ultimately leading to an increased susceptibility to predation as bats try to fly through the gated passage (Clark et al. 1996; Tuttle 1977, 1999; White and Seginak 1987). Of the 36 exit observations (Table 3), attempted predation (by an opossum, *Didelphis marsupialis*) was noted only once, and it resulted in the latest emergence noted during the entire study (cave #1; Fig. 5). The cave has an external grill over the entrance that is now left open year-round. An internal gate structure is presently located 12 m within the cave passage.

Cave biologists in Oklahoma have videotaped exit flights of gray bats through internally gated passages with no noticeable effect on bat flight (S. L. Hensley, personal communication), paralleling observations shown here. Many inferences are made in the literature on the inherent effects of gates on bat flight and increased susceptibility to predation. Distinctions must be made, however, between structures that are placed external to a cave entrance that are obsolete and known to affect bat flight (Ludlow and Gore 2000) and those that are currently placed within cave passages (Martin et al. 2000). It is speculated that relatively small colony sizes (<30,000) and small gated passages (1.4 – 15 m^2) used in this study contributed to dampening a perceived effect that internal positioning of grill structures have on bat flight and predation. This dampening must be considered when using internally designed gates to protect larger colonies of cave-dwelling gray bats and Indiana bats, requiring larger gated passages that are typical in other areas of these species' ranges.

Data and observations from these experiments show that stable populations of obligate cave-dwelling bats are found in caves protected with internally placed gate systems (Martin et al. 2000; Puckette 2000). Data indicate that these systems do not impede or delay exit flights of colonies of gray bats of 8,000-30,000 individuals. Evidence does not suggest that increased predation results from the presence of an internal gate system. It is recommended that current internal gate designs that are appropriately placed and allow persistent airflow within a cave passage be considered as a viable management option to eliminate casual or persistent human disturbance of vulnerable maternity and hibernating colonies of bats.

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Table 1. Mean ambient (air) temperatures in three caves gated with interior gate systems and three open passage caves. Each value represents a mean (n = 336) of observations recorded every 30 minutes for seven consecutive days (S1999 = Summer 1999, S2000 = Summer 2000, Winter 99-00 = Winter 1999-2000, W2001 = Winter 2001).

Cave No.	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	11.66
		35-60m	13.83	14.03	9.81	12.30
		>60m	13.77	13.98	14.35	12.99
3	Gated	<35m	14.00	14.51	11.66	14.51
		35-60m	13.90	14.49	12.30	14.49
		>60m	13.69	14.04	12.99	14.04
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

Table 2. Mean substrate (rock) temperatures in three caves gated with interior gate systems and three open passage caves. Each value represents a mean of (n = 336) observations recorded every 30 minutes for seven consecutive days (S1999 = Summer 1999, S2000 = Summer 2000, Winter 99-00 = Winter 1999-2000, W2001 = Winter 2001).

Cave No.	Gated/Open	Distance	S1999	S2000	W99-00	W00-01
		<35m	15.48	15.72	6.13	4.72
1	Gated	35-60m	16.41	16.02	13.34	11.95
		>60m	14.54	14.76	13.52	13.08
		<35m	13.98	14.00	12.00	9.60
2	Gated	35-60m	14.06	13.92	10.65	10.86
		>60m	13.73	14.01	13.89	13.45
		<35m	14.08	14.74	11.72	12.26
3	Gated	35-60m	14.04	14.47	12.30	10.86
		>60m	13.68	14.26	13.33	12.13
		<35m	14.35	14.71	11.21	9.11
4	Open	35-60m	14.19	14.38	12.06	10.10
		>60m	14.14	14.85	13.45	13.01
		<35m	13.06	13.16	11.47	9.72
5	Open	35-60m	12.44	12.64	12.31	10.97
		>60m	13.30	13.82	12.96	12.05
		<35m	17.36	14.21	13.04	6.31
6	Open	35-60m	14.65	13.56	13.79	9.82
		>60m	15.34	14.02	14.02	12.91

Table 3. Observations of exit flights for colonies of gray bats from six caves in northeastern Oklahoma. Values indicate number of minutes past official sunset. The first value listed indicates minutes past sunset when >30 bats first exited within a 60 second period. The second value indicates minutes past sunset when >60 bats first exited within a 60 second period.

Cave No.	1999 Obs. 1	1999 Obs. 2	1999 Obs. 3	2000 Obs. 4	2000 Obs. 5	2000 Obs. 6
1	32/39	23/28	16/18	25/27	16/19	21/23
2	8/12	10/13	0/2	12/16	13/16	20/21
3	9/12	13/15	19/20	9/13	11/20	24/27
4	7/8	13/15	16/17	12/14	10/13	12/18
5	26/28	22/25	20/21	18/23	15/18	12/14
6	14/17	22/26	13/17	16/17	20/21	15/19

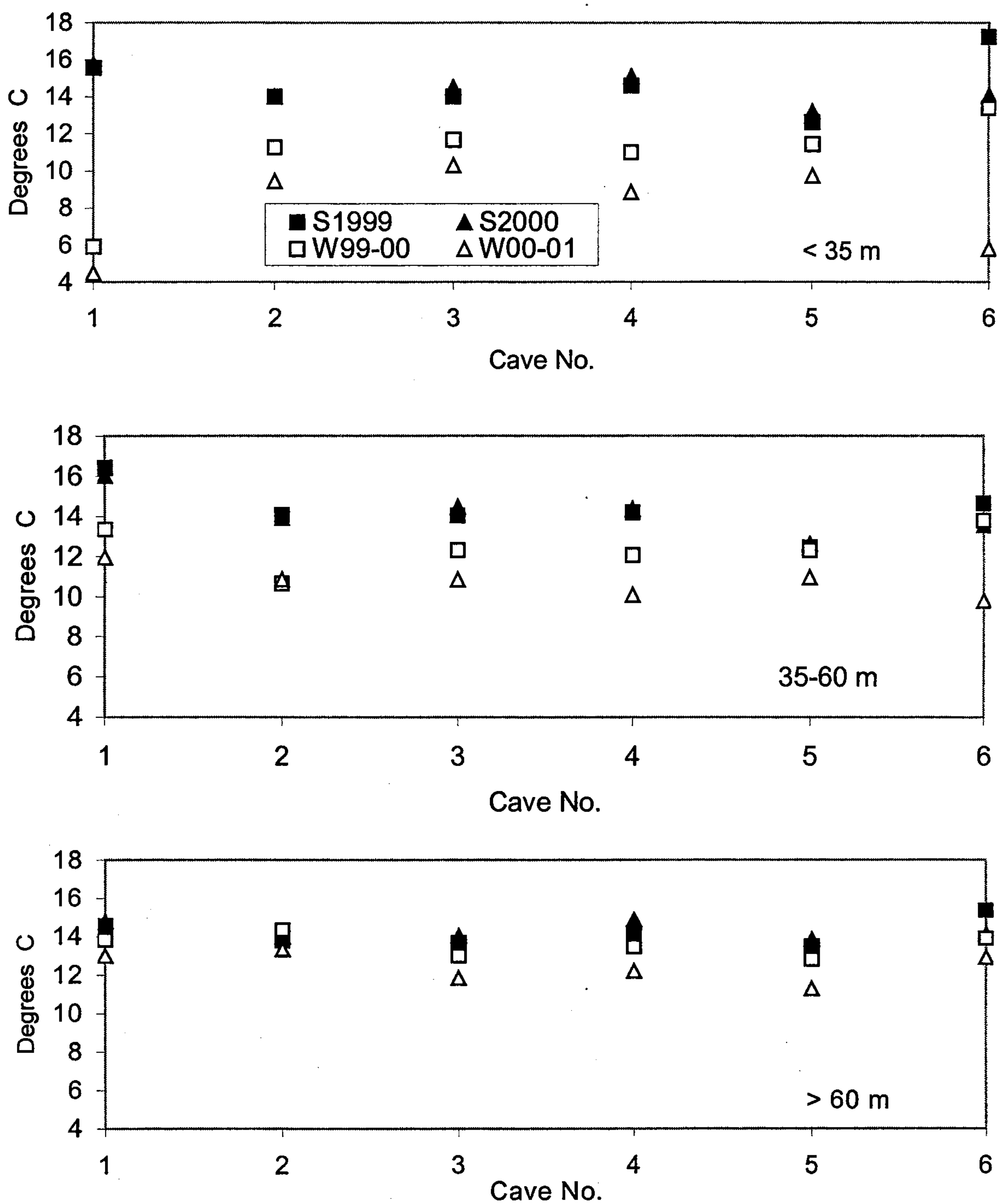

Figure 1. Summer and winter air temperature in three gated caves (1-3) and three open-passage caves (4-6) at three distances inside each entrance. Each data point represents a mean of 336 observations collected every 30 minutes for seven consecutive days.

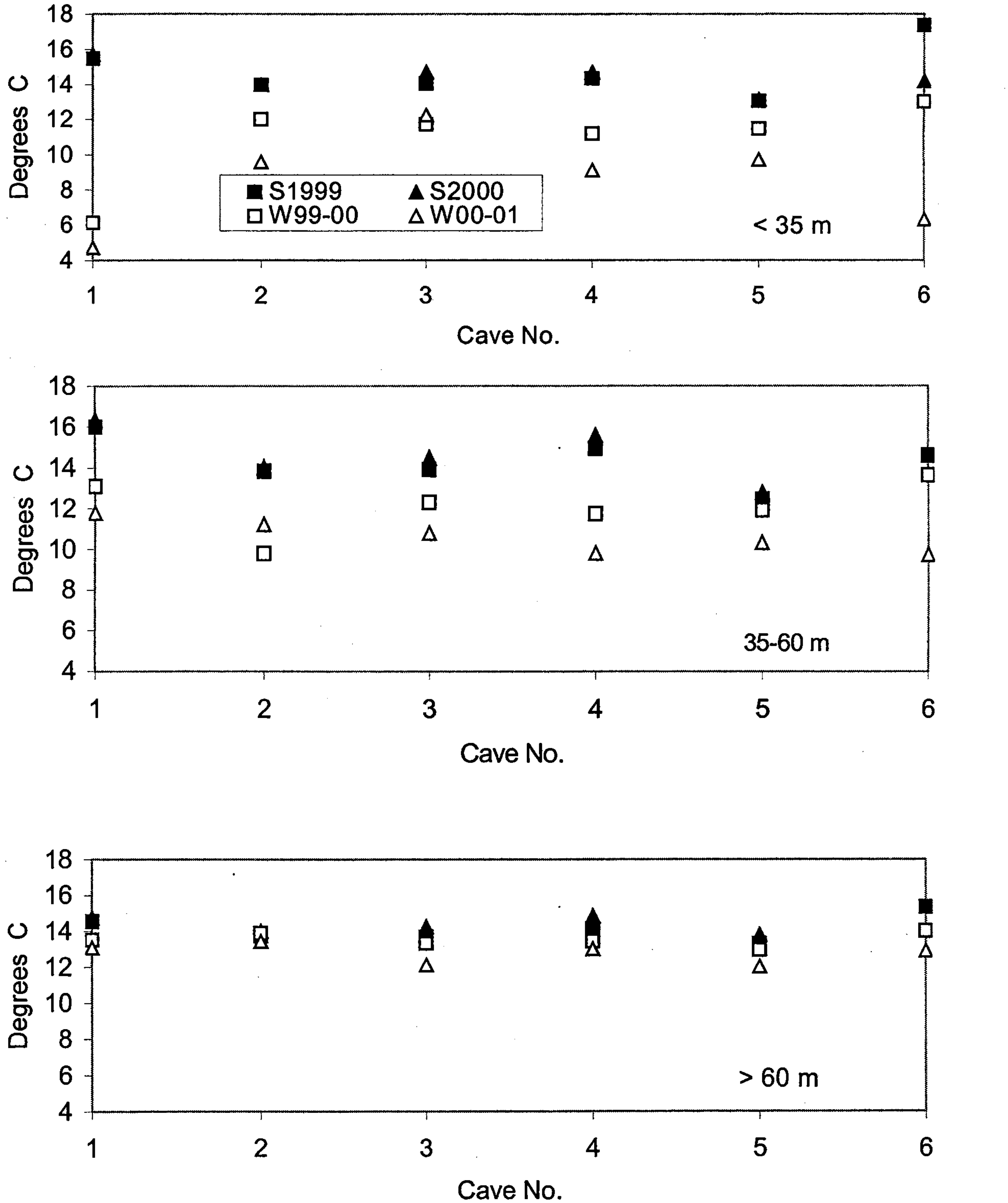

Figure 2. Summer and winter substrate (rock) temperature in three gated caves (1-3) and three open-passage caves (4-6)) at three distances inside each entrance. Each data point represents a mean of 336 observations collected every 30 minutes for seven consecutive days.

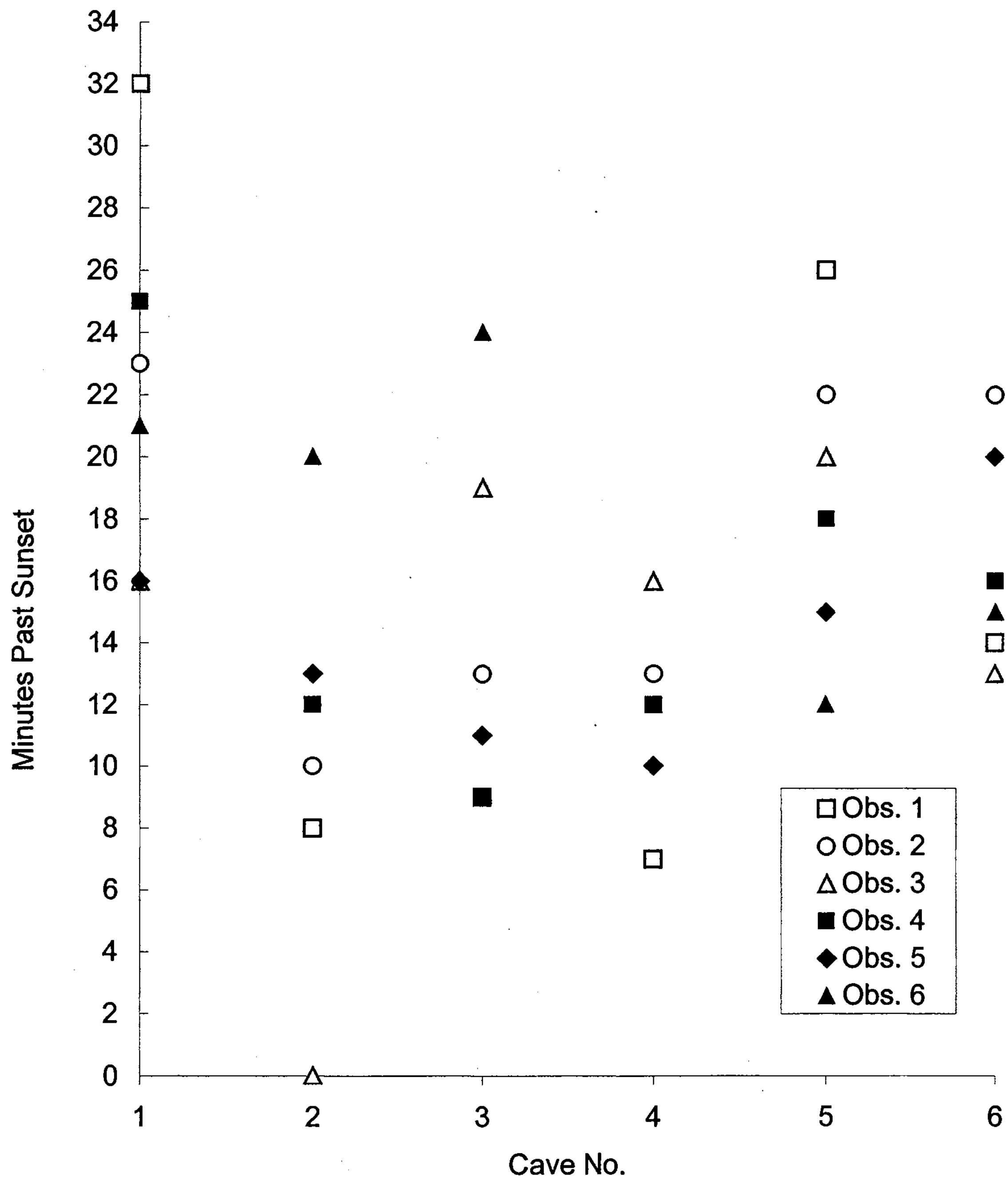

Figure 3. Timing of initiation of exit flights by colonies of gray bats at six caves in northeastern Oklahoma. Caves 1-3 contained internal gating systems for colony protection, and caves 4-6 had open passages. Data points represent time in minutes past sunset when 30 bats exited the cave in a 60 second period. Three observations were taken in summer 1999 and 2000 for each cave.

CHAPTER II

PRE-GATING AND POST-GATING CLIMATE IN TWO CAVES IN EASTERN OKLAHOMA

Abstract

Persistent or casual human disturbance incurred by bats in maternity caves and hibernacula has been implicated as a major cause for the decline in populations of most cave-dwelling bats. Efforts intended to eliminate disturbance resulting from human entry to these caves typically are accomplished by construction of gates at cave entrances. In northeastern Oklahoma, 24 entrances to caves presently are protected from human entry with internal "dark-zone" gates. Effects of internal cave gates on resident bats and climate of cave interiors have not been measured completely. Alterations in cave climate may affect life-history characteristics of bats such as body temperature, metabolic rates, fetal and neonatal development, and thermoregulation. In this study, long-term seasonal (summer and winter) ambient conditions were monitored at specific distances inside two caves (OK-13 and OK-220) in northeastern Oklahoma before and after management efforts modified their respective cave passages. Observations of internal cave climate were also collected for 7 days immediately before and after each modification. Differences in mean ambient (air) and substrate (rock) temperatures before and after passage/entrance manipulation in summer were rare. However, differences in these temperatures in winter were more common. No differences in ranges of ambient and substrate temperatures occurred regardless of season or cave. Differences occurred in

ambient and substrate temperatures before and after an internal gate system was installed within the passage of cave OK-13. Differences occurred in ambient and substrate temperatures before and after entrance and passage manipulation in cave OK-220 15 m inside the entrance, but not at locations deeper into the cave passage.

Introduction

About 18 of the 45 species of bats found in North America rely substantially on caves throughout the year, and 13 use caves year-round (McCracken 1989). These caves are used as winter hibernacula, stopover roost sites during migration, summer roost sites, or maternity sites where adult females give birth to their young. All North American bats listed as endangered or threatened by the U.S. Fish and Wildlife Service are cave-dwelling species or subspecies (McCracken 1989; Harvey et al 1999; Pierson 1999). Persistent or casual human disturbance at maternity caves and hibernacula has been implicated as a major cause for the decline in population of most cave dwelling-bats (Barbour and Davis 1969; Humphrey and Kunz 1976; Tuttle 1979; American Society Mammalogists 1992). Endangered or threatened populations cannot be viable with elevated mortality rates or poor recruitment as a result of disturbance (McCracken 1989; American Society of Mammalogists 1992). Conservation efforts concentrating on protecting these caves and the colonies of bats that they harbor are possibly the most important contemporary issue in bat conservation in the United States (American Society of Mammalogists 1992). These efforts usually are intended to eliminate disturbance resulting from human entry to these caves. Protection typically is accomplished by constructing gates at cave entrances, fencing cave entrances, placing warning signs at entrances, and maintaining a close and positive rapport with private landowners. Protection for populations of cave-dwelling bats by placing gates in entrances of caves can be an effective, immediate, and long-term method to deter human access to critical bat roosts (Humphrey 1978; Tuttle 1977; Tuttle and Stevenson 1977).

Populations of bats are presently protected with internal gate systems at 24 entrances to caves in northeastern Oklahoma. Seven of those caves have been inhabited historically by colonies of gray bats (*Myotis grisescens*). Thirteen entrances to caves inhabited by populations of Ozark big-eared bats (*Corynorhinus townsendii ingens*), big brown bats (*Eptesicus fuscus*), eastern pipistrelles (*Pipistrellus subflavus*), northern bats (*Myotis septentrionalis*), and a single hibernaculum of Indiana bats (*Myotis sodalis*) are protected similarly. Four caves that contain populations of the Ozark blind cavefish (*Amblyopsis rosae*) and Ozark blind crayfish (*Cambarus* sp.) also are protected from human entry by internal gates.

Three cave-dwelling species of bats found in eastern Oklahoma have been federally listed by the U.S. Fish and Wildlife Service: Ozark big-eared bat, gray bat, and Indiana bat. Populations of these bats that are protected with internal gates are located in Adair, Delaware, Cherokee, Leflore, and Ottawa counties of Oklahoma. Population estimates of bats at each of these caves before installation of gates in 1981 and post-installation estimates from 1999 suggest that each cave continues to be used by resident bat populations (Martin et al. 2000).

Although placement of gates within "dark zones" of cave passages may be the most effective method to deter human access to critical bat roosts, their effects on resident bats and microclimate of cave interiors have not been measured completely (Tuttle 1977; Tuttle and Stevenson 1977; Humphrey 1978; Richter et al. 1993). Various designs of gate construction and resulting effects on bat flight have been tested (White and Seginak 1987; Ludlow and Gore 2000). However, effects that gates have on the microclimate of cave interiors has not.

The intent of this study was to compare abiotic (ambient temperature, substrate temperature, relative humidity, dew point, and airflow) variables in two caves before and after various management efforts that altered each cave's entrance occurred. Given present use of caves with manipulated passages and entrances in Oklahoma by colonial bats that exhibit stable populations, I predicted minimal impacts on the climate of these cave interiors by management efforts altering each cave's entrance.

Materials and Methods

Cave OK-13

Long-term Seasonal Observations.– A summer population of about 14,000 gray bats have historically used cave OK-13 located in Ottawa County, Oklahoma (Martin et al. 2000). Lactating females and volant young were captured in a harp trap at the cave's entrance in July 1999 indicating use by a maternity colony of gray bats. A 9-m^2 internal gate system was installed 12 m within the cave passage in April 2000 to provide protection from human entry.

Warm-season climate variables (ambient temperature, substrate temperature, dew point, and relative humidity) were monitored within the cave 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 system was installed.

Climate variables were measured using HOBO H8 continuous data loggers (Onset Computer Corporation, Bourne, Maine). Three stations of data loggers were placed at specific distances (20 m, 40 m, 70 m) inside the cave entrance coinciding with historical locations of bat roost sites. One data logger at each station collected ambient temperature, relative humidity, and dew-point temperature. A second data logger monitored substrate temperature using an external probe placed in a hole drilled 1 cm into the rock substrate. Data loggers were attached together and suspended within 25 cm of the cave ceiling. If the cave ceiling could not be reached, data loggers were suspended from a rock ledge about 1.5 m from the cave floor.

Difficulty in recording relative humidity occurred when logger sensors became saturated in the high-humidity cave environments. When that occurred, readings exceeded 100% and were considered inaccurate by the manufacturer. When recorded dew-point observations were lower than ambient temperatures, they were used to calculate relative humidity. A combination of actual relative humidity recordings and those that were obtained by using dew point and ambient temperatures resulted in a scattered representation of ambient cave humidity. Although useful for anecdotal inferences, they were not suitable for statistical comparisons.

To establish units for statistical analysis, observations for each of the 6 weeks were combined into a mean of 336 observations/week for ambient (Table 1) and substrate (Table 2) temperatures. A split-plot ANOVA (SAS Institute Inc. 1999) compared cave climate temperature means before and after installation of the internal gate system. 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 (20 m, 40 m, 70 m). As a measure of variance, the temperature range for each mean was determined and compared between gated and open-passage conditions using the same randomized complete-block ANOVA parameters. Statistical significance for this and all subsequent comparisons was determined at $P < 0.5$.

Short-term Observations.– Additional observations were collected immediately before and after the internal gate system was installed within the cave passage. Due to a large cave passage area and associated logistical difficulties in constructing a large gate system, installation of an internal gate inside cave OK-13 spanned a period of 6 weeks in March-April 2000. Therefore, monitoring ambient and substrate temperatures before construction and immediately after completion of a gate system actually spanned an 8-week period rather than the planned 2-week period.

Ambient and substrate temperatures were recorded every 30 minutes for 7 consecutive days before installing the gate system. Data loggers within the cave passage were located at 20 m and 40 m inside the cave entrance. Ambient conditions were not recorded during the period when actual construction took place. Post-gating observations were recorded every 30 minutes for 7 consecutive days after installation of the gate system was completed. To establish units for statistical analysis, recordings for each day were combined into a mean of 48 observations/day for ambient and substrate temperatures (Table 5). A split-plot ANOVA (SAS Institute Inc. 1999) was used to compare short-term observations of cave climate before and after installation of the internal gate system. The main unit factor was open/modified airflow, and the split unit factor was distance inside each cave entrance where climate was monitored (20 m, 40 m, 70 m). As a measure of variance, the temperature range for each mean was determined and compared between gated and open-passage conditions using the same split-plot ANOVA parameters.

Cave OK-220

Long-term Seasonal Observations.– Past landowners of cave OK-220 located in Adair County, Oklahoma, had covered the < 2-m^2 entrance with a ¼" thick, 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. Remarkably, the cave was annually used as a hibernaculum by a small population of 100-200 eastern pipistrelles. Old guano accumulations suggest that a small population of a colonial species, probably gray bats, historically used the cave as a roost site. It was suspected that presence of the solid iron door restricted access to roost sites by bats and that airflow into and out of the cave was obstructed resulting in a suboptimal ambient environment conducive to increased utilization. I received permission from the current landowner to remove the iron door from the cave entrance in March 2000. An internal gate system covering 1.5 m^2 was constructed and installed 7 m within the cave passage in April 2001.

This progression of management efforts provided a unique opportunity to measure ambient climatic variables before and after various treatments were applied to a cave entrance. Climate variables (ambient temperature and substrate temperature) were measured with the cave's airflow obstructed by the iron door for 6 consecutive weeks in September-October 1999. Data also were collected for 6 consecutive weeks under obstructed conditions in March-April 2000. After the obstructive door was removed and natural airflow restored, seasonal observations were collected again for 6 consecutive weeks in August-September 2000 and March-April 2001.

Climate variables were measured as outlined above, but at different distances (15 m, 30 m, 70 m) inside the cave entrance. To establish units for statistical analysis, recordings for each week were combined into a mean of 336 observations/week for ambient (Table 3) and substrate (Table 4) temperatures. A split-plot ANOVA (SAS Institute Inc. 1999) compared cave climate temperatures before and after removal of the obstructive iron door. Main unit factors were season (summer and winter) and open/obstructed airflow, and the split unit factor was distance inside each cave entrance where climate was monitored. As a measure of variance, the temperature range for each mean was determined and compared between obstructed and open-passage conditions using the same split-plot ANOVA parameters.

Short-term Observations.– Observations were made immediately before and after the iron door was removed from the cave entrance in April 2000.

Ambient and substrate temperatures were recorded every 30 minutes for 7 consecutive days before and after removal of the door. Data logger locations within the cave passage coincided with those used during long-term observations (15 m, 30 m, 70 m). Ambient conditions were not recorded during the day that actual removal of the obstruction took place. To establish units for statistical analysis, recordings for each day were combined into a mean of 48 observations/day for ambient and substrate temperatures (Table 6). A split-plot ANOVA (SAS Institute Inc. 1999) compared short-term observations of cave climate before and after removal of the obstructive iron door. The main unit factor was open/obstructed airflow, and the split unit factor was distance inside each cave entrance where climate was monitored (15 m, 30 m, 70 m). As a measure of variance, the temperature range for each mean was determined and compared between obstructed and open-passage conditions using the same split-plot ANOVA parameters.

Internal ambient observations were again collected immediately before and after a 1.4-m^2 internal gate system was installed 7 m within the cave passage in April 2001. Ambient temperatures, substrate temperatures, and airflow were recorded every 30 minutes for 7 consecutive days before and after installing the gate system. Logger locations monitoring temperatures within the cave passage coincided with those used during previous observations (15 m, 30 m, 70 m).

Airflow was monitored using a sonic anemometer (Handar Instruments, Sunnyvale, California) placed 10 m inside the cave entrance. Air moved into the cave from outside, thus flowing through the gate after its installation. Ambient conditions were not recorded during the day actual construction took place. To establish units for statistical analysis, recordings for each day were combined into a mean of 48 observations/day for ambient temperatures, substrate temperatures (Table 7) and airflow (Table 8). A split-plot ANOVA (SAS Institute Inc. 1999) compared short-term observations of cave climate before and after installation of the internal gate system. The main unit factor was open/modified airflow, and the split unit factor was distance inside each cave entrance where climate was monitored. As a measure of variance, the temperature range for each mean was determined and compared between open-passage and gated conditions using the same split-plot ANOVA parameters. A complete-randomized ANOVA fitting a two-variance model compared rates of airflow before and after the internal gate system was installed.

Results

Cave OK-13

Long-term Seasonal Observations.– There were main unit effects and interaction between season (summer and winter) and open/manipulated passage. No differences occurred in mean ambient temperatures at any distance (20 m: $F = 0.99$, $df = 1{,}59.5$, $P = 0.33$; 40 m: $F = 0.38$, $df = 1{,}59.5$, $P = 0.53$; 70 m: $F = 1.95$, $df = 1{,}59.5$, $P = 0.16$) between September-October 1999 in natural airflow conditions and September-October 2000 when the passage was gated with an internal gate system (Fig. 1). Within the same season, the substrate temperature mean was cooler after passage manipulation at a distance of 20 m (F = 5.37, df = 1,59.5, P = 0.02) but did not differ at 40 m (F = 0.00, df = 1,59.5, P = 0.99) or 70 m (F = 1.37, df = 1,59.5, P = 0.25; Fig. 2).

Ambient temperature means during winter between natural airflow conditions (January-March 2000) and gated airflow (January-March 2001) were cooler after passage manipulation and differed at all three locations (20 m: F = 4.89, df = 1,59.5, P = 0.03; 40 m: F = 6.43, df = 1,59.5, P = 0.01; 70 m: F = 4.47, df = 1,59.5, P = 0.04; Fig. 1). Substrate temperature means were also cooler at 20 m (F = 4.86, df = 1,59.5, P = 0.03) and 40 m (F = 6.25, df = 1,59.5, P = 0.02) but not at 70 m (F = 3.16, df = 1,59.5, P = 0.08; Fig. 2).

No effects of gating occurred for the ranges of ambient (F = 0.14, df = 1,20; P = 0.72) or substrate (F = 0.34, df = 1,20; P = 0.57) temperatures. Interaction between season and gated/open passage conditions did not occur for ranges in ambient or substrate temperatures.

Short-term Observations.– Interaction occurred between gated/open-passage conditions and distances inside the cave entrance. Mean ambient temperatures recorded 7 days before and 7 days after installation of an internal gate system differed at distances of 20 m (F = 36.02, df = 1,22.1, P <.0001) and 40 m (F = 5.17, df = 1,22.1, P = 0.03). Similarly, mean substrate temperatures differed at 20 m (F = 20.04, df = 1,22.1, P = .0007) and 40 m (F = 20.40, df = 1,22.1, P = 0.0007; Fig. 3). Mean ambient and substrate temperatures were warmer after installation of the gate system at each distance.

Cave OK-220

Long-term Seasonal Observations. – Interaction occurred between season (summer and winter) and open/manipulated passage. No differences occurred in mean ambient temperatures at any distance (15 m: $F = 1.29$, $df = 1{,}52.5$, $P = 0.26$; 30 m: $F = 0.18$, $df = 1{,}52.5$, $P = 0.67$; 70 m: $F = 0.28$, $df = 1{,}52.5$, $P = 0.60$) between September-October 1999 when airflow was obstructed and August-September 2000 when the passage was unobstructed (Fig. 4). Within the same season, no differences occurred in mean substrate temperatures at 15 m ($F = 1.09$, $df = 1{,}51.1$, $P = 0.30$), 30 m ($F = 0.10$, $df = 1{,}51.1$, $P = 0.75$), or 70 m ($F = 0.18$, $df = 1{,}51.1$, $P = 0.67$; Fig. 5).

Mean ambient temperatures during winter-early spring months between obstructed airflow (February-April 2000) and unobstructed airflow (February-April 2001) were cooler after removing the iron door and differed at 15 m ($F = 6.70$, $df = 1{,}52.5$, $P = 0.01$) and 30 m ($F = 5.32$, $df = 1{,}52.5$, $P = 0.03$), but not at 70 m ($F = 0.15$, $df = 1{,}52.5$, $P = 0.70$; Fig. 4). Similarly, mean substrate temperatures during those same comparisons were cooler after restoring natural airflow and differed at 15 m ($F = 18.07$, $df = 1{,}51.1$, $P < 0.0001$) and 30 m ($F = 7.19$, $df = 1{,}51.1$, $P = 0.01$), but not at 70 m ($F = 0.19$, $df = 1{,}51.1$, $P = 0.66$; Fig. 5).

No effects of obstruction occurred in the ranges for ambient ($F = 0.16$, $df = 1{,}20$; $P = 0.69$) or substrate ($F = 2.23$, $df = 1{,}20$; $P = 0.15$) temperatures. Interaction between season and gated/open passage conditions did not occur for ranges in ambient or substrate temperatures.

Short-term Observations.– Main unit interaction (distance and open/obstructed airflow) occurred when comparing mean temperatures 7 days before and 7 days after the iron door was removed from the cave entrance in April 2000. Temperature means were warmer and differed at 15 m for ambient ($F = 22.87$, $df = 1,32.9$, $P < 0.0001$) and substrate temperatures ($F = 49.61$, $df = 1,32.9$, $P < 0.0001$; Fig. 6). No differences existed in ambient temperatures at 30 m ($F = 0.62$, $df = 1,32.9$, $P = 0.43$) or 70 m ($F = 0.01$, $df = 1,32.9$, $P = 0.92$). Similarly, substrate temperatures did not differ at 30 m ($F = 3.21$, $df = 1,32.9$, $P = 0.08$) and 70 m ($F = 0.06$, $df = 1,32.9$, $P = 0.81$; Fig. 6). No effect of obstruction to the cave entrance occurred for ambient temperature ranges ($F = 2.43$, $df = 1,12$; $P = 0.15$).

Similar results occurred when comparing ambient and substrate temperatures recorded 7 days before and 7 days after installation of an internal gate system in the cave passage in April 2001. Temperature means were warmer at 15 m for ambient ($F = 28.60$, $df = 1,33.6$, $P < .0001$) and substrate temperatures ($F = 47.11$, $df = 1,31.2$, $P < .0001$; Fig. 7). No differences existed in ambient temperatures at 30 m ($F = 1.12$, $df = 1,33.6$, $P = 0.30$) or 70 m ($F = 0.03$, $df = 1,33.6$, $P = .86$). Similarly, substrate temperatures did not differ at 30 m ($F = 3.35$, $df = 1,31.2$, $P = .08$) and 70 m ($F = 0.08$, $df = 1,31.2$, $P = 0.79$; Fig. 7). No effect of gating the cave passage occurred in the ANOVA for ambient temperature ranges ($F = 0.06$, $df = 1,13$; $P = 0.81$).

Airflow 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 ($F = 0.01$, $df = 1,11$, $P = 0.94$; Fig. 8). Airflow direction was recorded at 30-minute intervals to ensure that it was flowing into the cave from outside through the internal gate system.

Discussion

Effects that external climatic factors such as temperature, atmospheric pressure, and airflow have on internal ambient cave environments are well documented (Tuttle and Stevenson 1977; Richter et al 1993). Although influenced directly by changes in temperature and atmospheric pressure, airflow may be most influential in dictating ambient conditions inside of caves. Tuttle and Stevenson (1977) discussed important effects of cave structure and elevational displacement of internal air volume on ambient cave conditions. From a biological standpoint, these factors combine to create habitats that correlate to high evolutionary specialization typically exhibited by obligate cave fauna. Peck (1998) noted $\geq$ 1,353 (425 aquatic, 928 terrestrial) animal species that were restricted to subterranean habitats in the U.S. and Canada. In obligate cave-dwelling species of bats, microclimate variables are most influential during hibernation and in summer maternity colonies. It is evident that distribution of caves containing appropriate internal ambient conditions plays an important role in distribution and ranges of cave-dwelling bat species (Tutttle and Stevenson 1977; Raesley and Gates 1987; Thomas 1995).

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. Poor thermoregulation in these bats may result in slow maturation, thus reducing survival and natality (Studier and O'Farrell 1972; Humphrey 1975).

A systematic assessment of impacts on the microclimate of the cave interiors by the installation of gate systems in caves throughout the United States is conspicuously missing. Characteristics of cave entrances that affect internal ambient conditions, including number of entrances, size of entrances, passage size, presence of water flow, air flow, and annual range of temperatures outside the cave (Tuttle and Stevenson 1977). It is also suspected that cave gates alter airflow in cave passages (Humphrey 1978; Richter et al. 1993; U.S. Fish and Wildlife Service 1984). Altered airflow, in turn, may affect ambient temperature, humidity, and substrate temperature. Designed experiments and quantitative data on effects of modifications to cave entrances on internal cave microclimates, such as cave gates, are limited to nonexistent (Richter et al. 1993). Surface and entrance characteristics between study caves are highly variable, and controlling for this variation to establish a sound experimental design can be difficult.

Warm-season Observations

During long-term, warm-season monitoring (September-October 1999, 2000) before and after passage/entrance manipulation, only a single significant difference occurred in mean ambient and substrate temperatures at cave OK-13 (T_s: 20 m), and no significant differences in either variable occurred at cave OK-220. Passage/entrance manipulations did not have an effect on temperature ranges during warm months. These study caves have a tendency to breath "outwardly" during warmer seasons when internal air is cooler than outside air and outside air is warmer than the mean annual surface temperature (MAST). An internally placed gate located 12 m inside the entrance to cave OK-13 and an obstructive iron door covering the entrance to cave OK-220 thus had minimal effects on warm-season ambient and substrate temperatures.

Cool-season Observations

As most caves in eastern Oklahoma, the study caves tend to breath "inwardly" in winter months when external air is cooler than internal air temperatures and cooler than MAST temperatures. If airflow were impeded in any manner by manipulating an entrance, it would be magnified in these months when external airflow is carried into the cave's interior. Significant differences in mean ambient and substrate temperatures occurred at all but one substrate logger location (70 m) in cave OK-13 between winter 2000 (open passage) and winter 2001 (gated). Only one monitoring location considered deep in the passage of cave OK-220 (70 m) showed no differences in mean ambient and substrate temperatures between obstructed observations in winter 2000 and unobstructed observations in winter 2001.

Cool-season minimum and maximum ambient temperature means that differed at cave OK-13 ranged from 12.99-13.86°C before the cave was gated and 11.99-13.46°C after gating. Ambient temperature means indicating significant differences at cave OK-220 during winter observations were 7.43-13.27°C when airflow was obstructed by an iron door and 5.80-13.16°C when open-passage conditions existed. Although statistically significant, these temperatures correspond closely with those observed at hibernating clusters of Ozark big-eared bats in Oklahoma (5.5-11.2°C; Clarke et al. 1996) and Arkansas (<12°C; Harvey and Barclay 1990), and those indicated for gray bats (6-11°; U.S.

Fish and Wildlife Service 1982). When ambient and substrate temperature ranges were compared in these study caves, no significant differences occurred between open-passage and manipulated passage conditions.

Except on rare occasions, colonial gray bats are historically absent from all caves in eastern Oklahoma during hibernation. Therefore, any significant differences in climatic conditions with biological implications caused by internal gate systems cannot be determined for that species. However, observations of hibernating populations of Ozark big-eared bats in caves with internal gate systems indicate stable numbers (Puckette 2000). These data and observations suggest that although narrow temperature means before and after entrance manipulation may be statistically significant, corresponding temperature ranges are not. In the case of caves OK-13 and OK-220, other factors such as external seasonal changes have a greater biological implications for habitation by endemic cave fauna.

Short-term Pre- and Post-manipulation Observations

Typical seasonal warming can explain significant changes in mean ambient and substrate temperatures that occurred between observations collected 7 days before initiating construction of an internal gate system and observations collected 8 weeks later after its completion. However, actual differences between minimum and maximum daily means during the entire monitoring period were only 1.23°C (20 m) and 0.41°C (40 m) for ambient temperatures and 1.10°C (20 m) and 0.47°C (40 m) for substrate temperatures. Clark et al. (1996) reported ambient temperature ranges of 5.5-11.2°C at hibernating clusters of Ozark big-eared bats in Oklahoma caves. Minimum and maximum temperature means at cave OK-13 before and after installation of the internal gate system were much more narrow in ambient (12.96-14.19°C) and substrate (12.81-13.91°C) temperatures at 20 m. Similar narrow temperature ranges occurred in mean ambient (13.22-13.63°C) and substrate (13.34-13.91°C) temperatures at 40 m. Although these temperature changes were statistically different, their biological implications on endemic cave fauna may be minimal.

Internal ambient and substrate temperature means 7 days before and 7 days after manipulations at cave OK-220 differed only at the monitoring station closest to the cave entrance (15 m). Airflow 10 m inside the cave entrance (3 m inside gate system), and ambient and substrate temperature ranges before and after installation of the internal gate system did not vary statistically. Differences in mean ambient and substrate temperatures at 15 m inside the cave entrance may be explained simply by variable climatic conditions that persist at this distance inside most cave passages. A lack of changes in mean daily airflow in this same region before and after gating is intriguing. Cave OK-220 had a single entrance that may have been more conducive to constant rates of airflow, as opposed to multiple entrances and distinct elevational changes creating greater variations in airflow. At this particular cave, manipulating the entrance and passage did not affect mean temperature variables at distances beyond 15 m, airflow within 3 m of the internally placed gate system, or temperature ranges inside the cave passage.

It is evident from these data that measurable impacts on warm-season microclimates of cave interiors by management treatments were minimal. These minimal impacts are substantiated by present bat colonies using caves in Oklahoma with manipulated passages and entrances that exhibit stable populations (Martin et al. 2000; Puckette 2000). Population estimates during maternity seasons in 2000 and 2001 at cave OK-13 were >12,000. These estimates were nearly identical to those collected before gating the passage (Grigsby et al. 1993).

An obvious gradient in effects of external climatic variables on internal climatic conditions exists in cave environments, being greater in the ecotonal environment near the entrance and narrowing as passage length reaches 30-40 m and beyond. Passage size, entrance size, entrance orientation (vertical vs. horizontal), number of entrances, and passage to entrance elevational configurations determine rate of airflow into and out of a cave ecosystem. These factors are affected by movement of large volumes of air in some caves, but lesser volumes in others (Tuttle and Stevenson 1977). It is apparent from my data that caves with modified entrances and passages, exhibiting what might be considered moderate to low volumes of airflow, show no changes in ambient and substrate temperature means or ranges when airflow moves outward in summer, and only slight changes in winter. It may be correct to assume, therefore, that appropriately placed internal gate systems that allow ample airflow would have no effects on resident maternity colonies and other summer colonies of bats.

An absence of large colonies of hibernating bats in eastern Oklahoma preclude management recommendations pertaining to gating cave passages in winter. 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. Based on data from these experiments, it is recommended that current internal gates designs that are appropriately placed and allow persistent airflow within a cave passage be considered as a viable management option. This tactic is particularly important when casual or persistent human disturbance is of primary concern.

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Table 1. Mean ambient (air) temperature during 6 consecutive weeks at cave OK-13 in Ottawa County, Oklahoma, in September-October 1999 and January-March 2000 under open passage conditions and in September-October 2000 and January-March 2001 after the passage was gated with an interior gate system. Each weekly value represents mean observations (n = 336) recorded every 30 minutes for 7 consecutive days.

Week No.	Monitoring Distance	T_a (Open) Sept-Oct 1999	T_a (Gated) Sept-Oct 2000	T_a (Open) Jan-Mar 2000	T_a (Gated) Jan-Mar 2001
1	20 m	16.36	16.63	13.15	12.61
	40 m	14.67	15.20	12.99	12.82
	70 m	16.45	16.39	13.89	13.47
2	20 m	16.35	16.11	12.99	12.68
	40 m	14.54	16.27	13.38	12.90
	70 m	15.18	15.39	13.37	13.46
3	20 m	16.46	15.64	13.03	12.64
	40 m	14.39	15.18	13.35	12.65
	70 m	14.82	15.99	13.84	13.39
4	20 m	15.79	15.64	13.12	11.99
	40 m	16.32	14.79	13.39	12.05
	70 m	14.66	15.62	13.85	13.01
5	20 m	15.60	14.90	13.15	12.29
	40 m	16.70	14.57	13.36	12.40
	70 m	14.72	15.31	13.86	13.05
6	20 m	15.24	15.16	13.04	12.44
	40 m	14.95	14.49	13.28	12.54
	70 m	15.50	15.05	13.82	13.09

Table 2. Mean substrate (rock) temperature during 6 consecutive weeks at cave OK-13 in Ottawa County, Oklahoma, in September-October 1999 and January-March 2000 under open passage conditions and in September-October 2000 and January-March 2001 after the passage was gated with an interior gate system. Each weekly value represents mean observations (n = 336) recorded every 30 minutes for 7 consecutive days.

Week No.	Monitoring Distance	T_s (Open) Sept.-Oct. 1999	T_s (Gated) Sept.-Oct. 2000	T_s (Open) Jan.-Mar. 2000	T_s (Gated) Jan.-Mar. 2001
1	20 m	16.21	16.11	12.90	12.84
	40 m	15.08	15.34	13.64	13.13
	70 m	16.24	16.04	13.94	13.60
2	20 m	16.20	15.90	12.66	12.01
	40 m	14.64	16.43	13.51	13.21
	70 m	15.07	15.15	13.88	13.58
3	20 m	16.86	15.58	12.69	12.39
	40 m	14.51	15.25	13.48	12.95
	70 m	14.77	15.79	13.84	13.54
4	20 m	16.07	15.30	12.80	12.18
	40 m	15.95	14.93	13.52	12.35
	70 m	14.61	15.43	13.82	13.22
5	20 m	15.62	14.76	13.00	12.03
	40 m	16.27	14.75	13.48	12.75
	70 m	14.67	15.17	13.82	13.20
6	20 m	15.28	15.07	12.97	12.22
	40 m	14.92	14.69	13.41	12.85
	70 m	15.33	14.89	13.77	13.23

Table 3. Mean ambient (air) temperature during 6 consecutive weeks at cave OK-220 in Adair County, Oklahoma, with an obstructive iron door over the cave entrance. Obstructed airflow temperatures were recorded in September-October 1999 and February-April 2000, and temperatures were collected again after the obstructive door was removed in August-September 2000 and February-April 2001. Each weekly value represents mean observations (n = 336) recorded every 30 minutes for 7 consecutive days.

Week No.	Monitoring Distance	T_a (Obstructed) Sept.-Oct. 1999	T_a (Open) Aug.-Sept. 2000	T_a (Obstructed) Jan.-Mar. 2000	T_a (Open) Jan.-Mar. 2001
1	15 m	14.20	14.07	7.43	5.80
	30 m	13.59	13.66	11.04	9.75
	70 m	13.97	14.12	13.12	12.91
2	15 m	14.20	14.21	7.87	7.45
	30 m	13.59	13.69	11.25	9.91
	70 m	13.93	14.14	13.15	12.94
3	15 m	14.12	14.46	10.56	6.40
	30 m	13.60	13.74	11.84	10.18
	70 m	13.88	14.15	13.23	12.95
4	15 m	13.67	14.36	9.49	6.44
	30 m	13.56	13.73	11.82	9.98
	70 m	13.86	14.17	13.26	13.00
5	15 m	12.81	14.42	10.19	9.23
	30 m	13.35	13.78	11.43	10.95
	70 m	13.82	14.18	13.22	13.11
6	15 m	13.20	14.15	10.28	12.60
	30 m	13.49	13.87	11.85	11.42
	70 m	13.83	14.14	13.27	13.16

Table 4. Mean substrate (rock) temperature during 6 consecutive weeks at cave OK-220 in Adair County, Oklahoma, with an obstructive iron door over the cave entrance. Obstructed airflow temperatures were recorded in September-October 1999 and February-April 2000, and temperatures were collected again after the obstructive door was removed in September-October 2000 and February-April 2001. Each weekly value represents mean observations (n = 336) recorded every 30 minutes for 7 consecutive days.

Week No.	Monitoring Distance	T_s (Obstructed) Sept.-Oct. 1999	T_s (Open) Sept.-Oct. 2000	T_s (Obstructed) Jan.-Mar. 2000	T_s (Open) Jan.-Mar. 2001
1	15 m	14.39	14.22	8.44	6.31
	30 m	13.53	13.56	11.01	9.82
	70 m	13.94	14.02	13.09	12.91
2	15 m	14.44	14.33	8.58	7.28
	30 m	13.57	13.59	11.16	10.05
	70 m	13.92	14.04	13.12	12.93
3	15 m	14.35	14.60	10.34	6.64
	30 m	13.61	13.72	11.62	10.06
	70 m	13.88	14.05	13.20	12.95
4	15 m	14.02	14.58	9.82	6.60
	30 m	13.59	13.74	11.71	10.03
	70 m	13.85	14.06	13.23	13.00
5	15 m	13.49	14.65	10.52	8.93
	30 m	13.48	13.76	11.47	10.69
	70 m	13.82	14.08	13.21	13.06
6	15 m	13.64	14.53	10.43	11.86
	30 m	13.55	13.74	11.65	11.34
	70 m	13.82	14.04	13.24	13.15

Table 5. Mean ambient (T_a) and substrate (T_s) temperatures at cave OK-13 in Ottawa County, Oklahoma, in April 2000. Temperatures were collected 7 days before (-) and after (+) installation of an internal gate system placed 12 m inside the cave entrance. Each daily value represents mean observations (n = 48) collected every 30 minutes over a 24-hour period.

Period (Days)	Airflow	Monitoring Distance	T_a	T_s	Period (Days)	airflow	Monitoring Distance	T_a	T_s
- 7	Open	20 m	12.96	12.81	+7	Gated	20 m	13.22	13.06
- 6	Open	20 m	13.01	12.89	+6	Gated	20 m	13.28	13.04
- 5	Open	20 m	13.06	12.94	+5	Gated	20 m	13.79	13.07
- 4	Open	20 m	13.05	12.97	+4	Gated	20 m	13.53	13.46
- 3	Open	20 m	13.05	12.97	+3	Gated	20 m	13.50	13.36
- 2	Open	20 m	13.04	12.95	+2	Gated	20 m	13.88	13.27
- 1	Open	20 m	13.05	12.97	+1	Gated	20 m	14.19	13.25
- 7	Open	40 m	13.22	13.34	+1	Gated	40 m	13.34	13.51
- 6	Open	40 m	13.23	13.36	+2	Gated	40 m	13.33	13.49
- 5	Open	40 m	13.25	13.37	+3	Gated	40 m	13.36	13.52
- 4	Open	40 m	13.26	13.39	+4	Gated	40 m	13.63	13.91
- 3	Open	40 m	13.27	13.39	+5	Gated	40 m	13.58	13.81
- 2	Open	40 m	13.26	13.39	+6	Gated	40 m	13.55	13.72
- 1	Open	40 m	13.27	13.39	+7	Gated	40 m	13.55	13.70

Table 6. Mean ambient (T_a) and substrate (T_s) temperatures at cave OK-220 in Adair County, Oklahoma, in April 2000. Temperatures were collected 7 days before (-) and after (+) removal of a solid iron door covering the cave entrance. Each daily value represents mean observations (n = 48) collected every 30 minutes over a 24-hour period.

Period (Days)	Airflow	Monitoring Distance	T_a	T_s	Period (Days)	Airflow	Monitoring Distance	T_a	T_s
- 7	Obstructed	15 m	9.53	10.42	+1	Open	15 m	11.51	11.24
- 6	Obstructed	15 m	9.26	9.87	+2	Open	15 m	10.35	10.73
- 5	Obstructed	15 m	10.47	10.32	+3	Open	15 m	11.04	10.93
- 4	Obstructed	15 m	10.66	10.58	+4	Open	15 m	12.45	12.01
- 3	Obstructed	15 m	10.41	10.47	+5	Open	15 m	12.08	11.82
- 2	Obstructed	15 m	10.54	10.50	+6	Open	15 m	11.19	11.31
- 1	Obstructed	15 m	10.69	10.65	+7	Open	15 m	10.52	10.94
- 7	Obstructed	30 m	11.20	11.43	+1	Open	30 m	11.81	11.82
- 6	Obstructed	30 m	11.20	11.29	+2	Open	30 m	11.78	11.73
- 5	Obstructed	30 m	11.66	11.46	+3	Open	30 m	11.99	11.80
- 4	Obstructed	30 m	11.90	11.64	+4	Open	30 m	12.15	11.94
- 3	Obstructed	30 m	11.85	11.67	+5	Open	30 m	11.50	11.75
- 2	Obstructed	30 m	11.86	11.69	+6	Open	30 m	11.69	11.70
- 1	Obstructed	30 m	11.88	11.73	+7	Open	30 m	11.88	11.74
- 7	Obstructed	70 m	13.21	13.20	+1	Open	70 m	13.29	13.26
- 6	Obstructed	70 m	13.21	13.20	+2	Open	70 m	13.28	13.25
- 5	Obstructed	70 m	13.23	13.21	+3	Open	70 m	13.30	13.27
- 4	Obstructed	70 m	13.27	13.23	+4	Open	70 m	13.33	13.29
- 3	Obstructed	70 m	13.27	13.24	+5	Open	70 m	13.22	13.24
- 2	Obstructed	70 m	13.28	13.24	+6	Open	70 m	13.24	13.23
- 1	Obstructed	70 m	13.29	13.25	+7	Open	70 m	13.26	13.24

Table 7. Mean ambient (T_a) and substrate (T_s) temperatures at cave OK-220 in Adair County Oklahoma in April 2000. Temperatures were collected 7 days before (-) and after (+) installation of an internal gate system placed 7 m inside the cave entrance. Each daily value represents mean observations (*n* = 48) collected every 30 minutes over a 24-hour period.

Period (Days)	Airflow	Monitoring Distance	T_a	T_s	Period (Days)	Airflow	Monitoring Distance	T_a	T_s
- 7	Open	15 m	8.46	7.83	+1	Gated	15 m	12.73	12.65
- 6	Open	15 m	5.97	6.82	+2	Gated	15 m	12.29	12.43
- 5	Open	15 m	8.98	8.26	+3	Gated	15 m	11.24	11.44
- 4	Open	15 m	9.80	9.29	+4	Gated	15 m	13.99	11.75
- 3	Open	15 m	9.67	9.26	+5	Gated	15 m	11.14	11.02
- 2	Open	15 m	10.23	10.03	+6	Gated	15 m	10.34	10.51
- 1	Open	15 m	11.34	10.96	+7	Gated	15 m	10.84	10.65
- 7	Open	30 m	10.04	10.12	+1	Gated	30 m	11.38	11.29
- 6	Open	30 m	10.18	10.10	+2	Gated	30 m	11.49	11.42
- 5	Open	30 m	10.81	10.41	+3	Gated	30 m	11.73	11.71
- 4	Open	30 m	11.17	10.68	+4	Gated	30 m	11.30	11.42
- 3	Open	30 m	11.42	10.89	+5	Gated	30 m	11.23	11.07
- 2	Open	30 m	11.51	11.19	+6	Gated	30 m	11.50	11.31
- 1	Open	30 m	11.50	11.44	+7	Gated	30 m	11.58	11.41
- 7	Open	70 m	13.00	13.01	+1	Gated	70 m	13.15	13.15
- 6	Open	70 m	13.00	13.00	+2	Gated	70 m	13.18	13.17
- 5	Open	70 m	13.06	13.03	+3	Gated	70 m	13.19	13.18
- 4	Open	70 m	13.12	13.06	+4	Gated	70 m	13.13	13.14
- 3	Open	70 m	13.17	13.09	+5	Gated	70 m	13.19	13.16
- 2	Open	70 m	13.21	13.12	+6	Gated	70 m	13.21	13.18
- 1	Open	70 m	13.20	13.15	+7	Gated	70 m	13.32	13.20

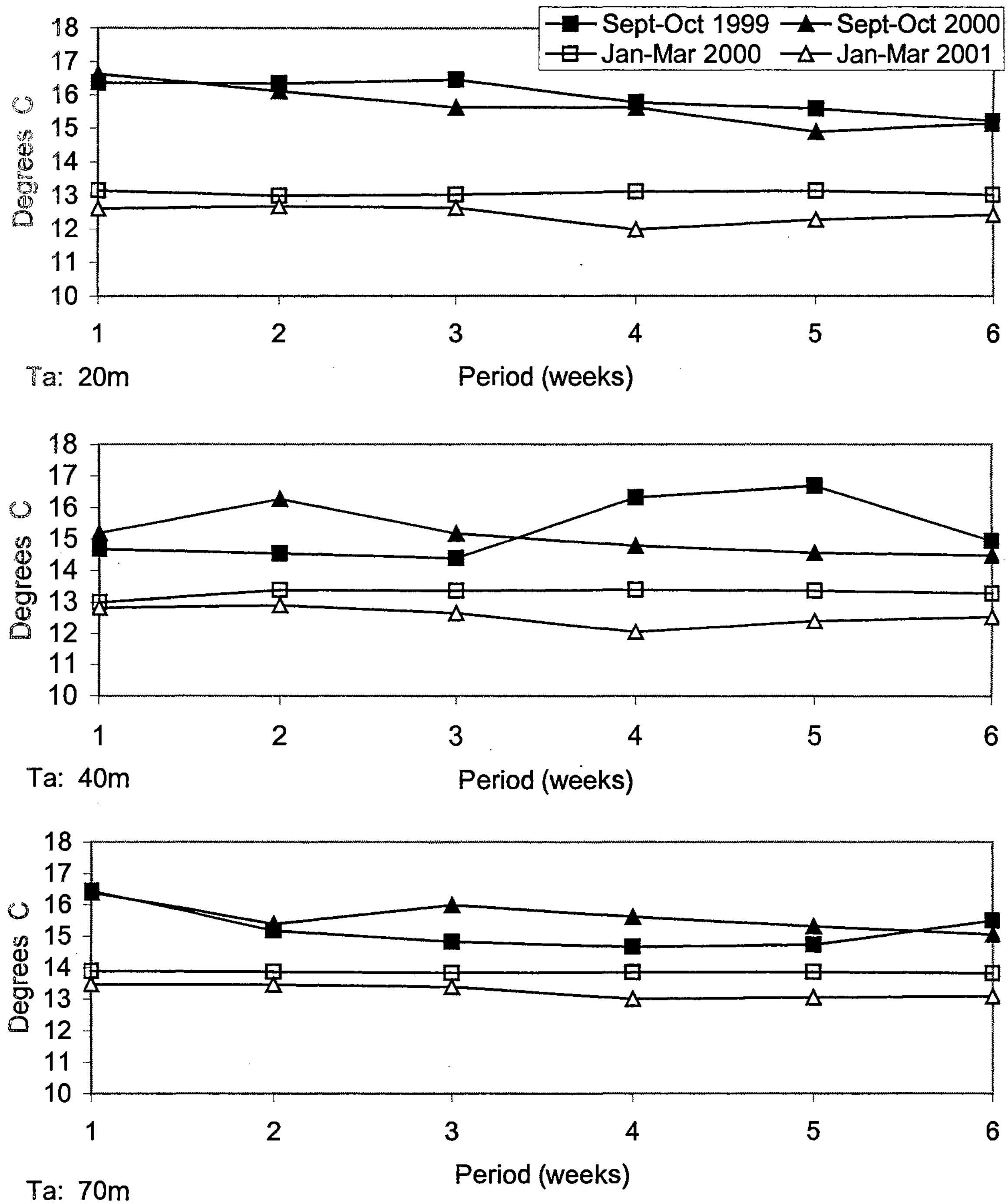
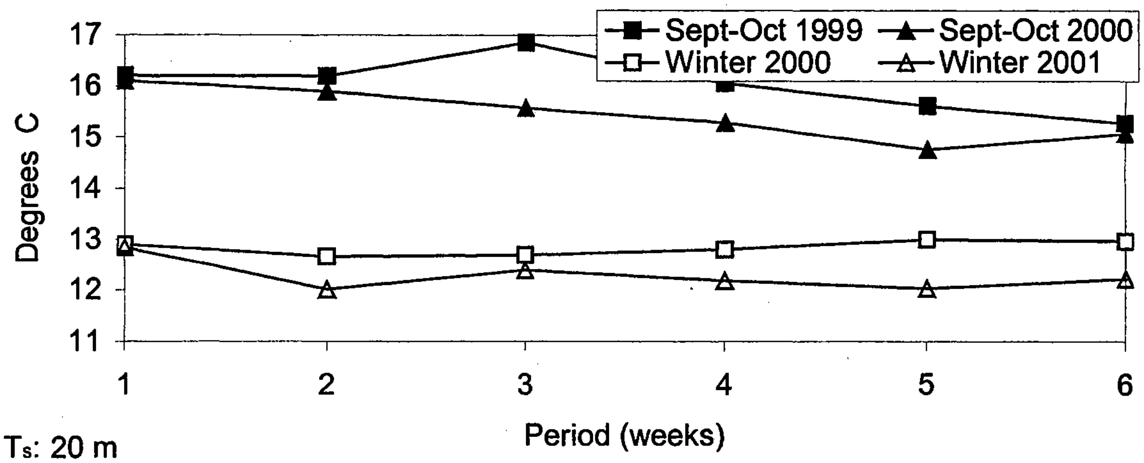


Figure 1. Ambient (air) temperature from cave OK-13 in Ottawa County, Oklahoma. Observations in summer 1999 and winter 2000 were during conditions of natural airflow into the cave. Subsequent observations in summer 2000 and winter 2001 were after an internal gate system was installed 12 m inside the cave passage. Each data point represents mean observations (*n* = 336) recorded every 30 minutes over a 7-day period (one week).

Figure 2. Substrate (rock) temperature from cave OK-13 in Ottawa County, Oklahoma. Observations during summer 1999 and winter 2000 were during conditions of natural airflow into the cave. Subsequent observations in summer 2000 and winter 2001 were after an internal gate system was installed 12 m inside the cave passage. Each data point represents mean observations (n = 336) recorded every 30 minutes over a 7-day period (one week).



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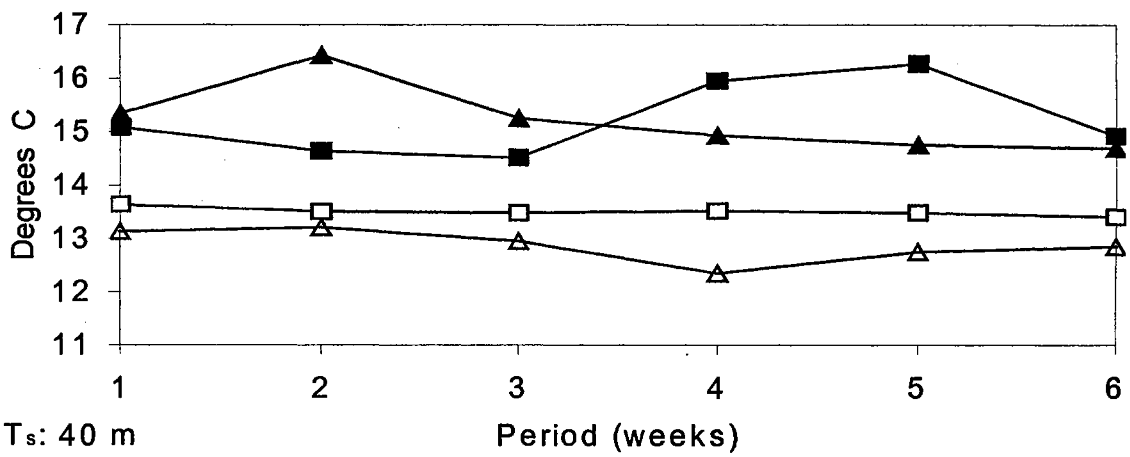

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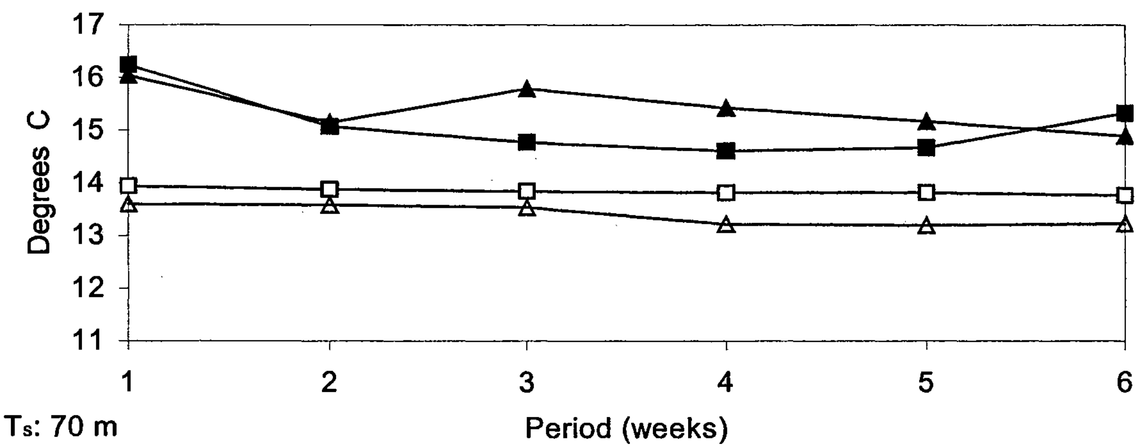

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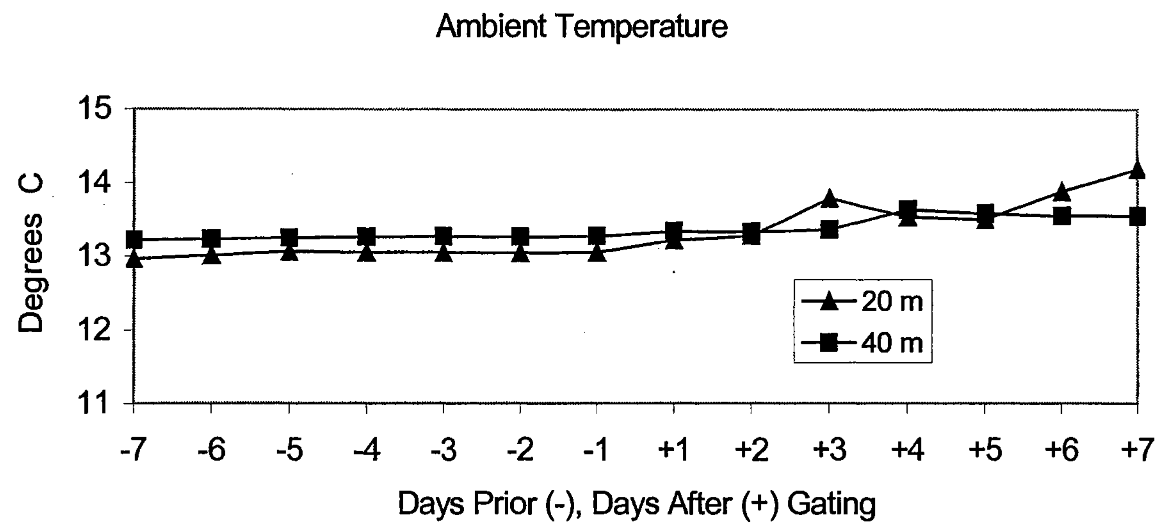


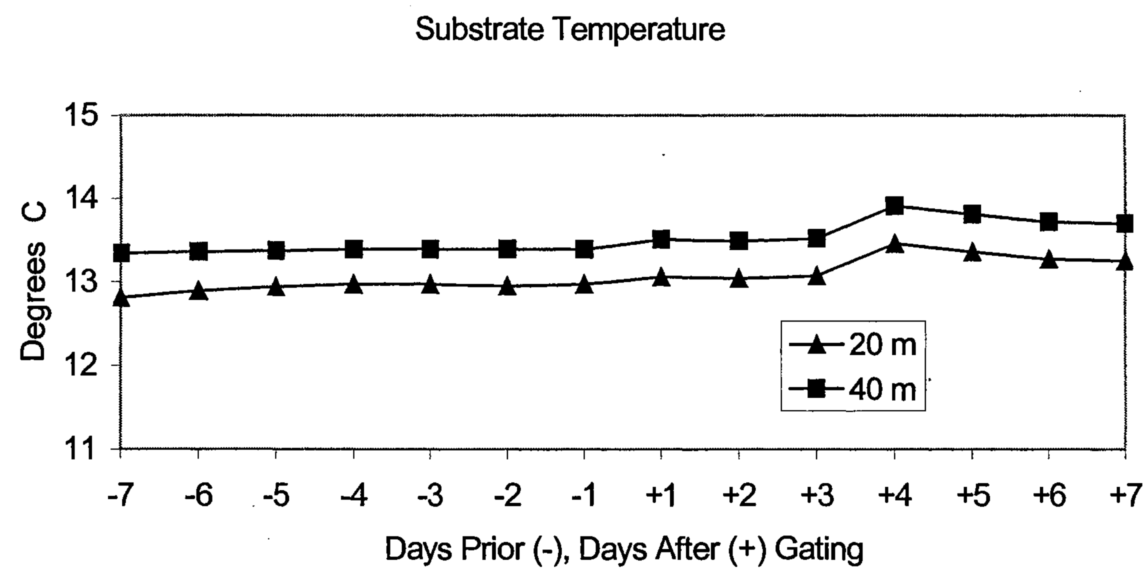
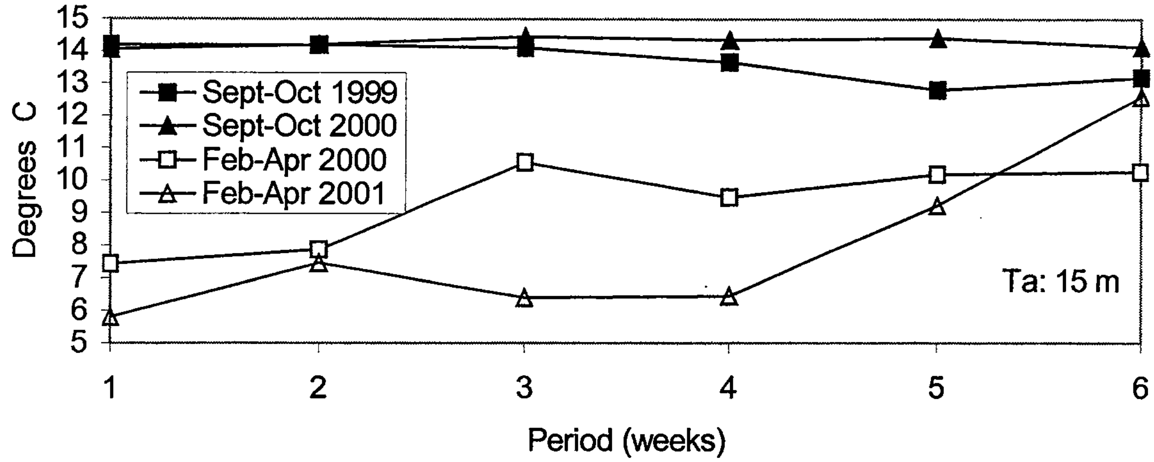


Figure 3. Ambient (T_a) and substrate (T_s) temperatures at cave OK-13 in Ottawa County, Oklahoma. Observations were made 7 days before and 7 days after an internal gating system was installed 12 m inside the cave entrance. Each data point represents mean observations (n = 48) recorded every 30 minutes for a 24-hour period.

Figure 4. Ambient (air) temperature from cave OK-220 in Adair County, Oklahoma, in summer 1999 and winter 2000 while natural airflow into the cave was obstructed by a solid iron door. Subsequent observations were made in 2000-2001 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 (one week).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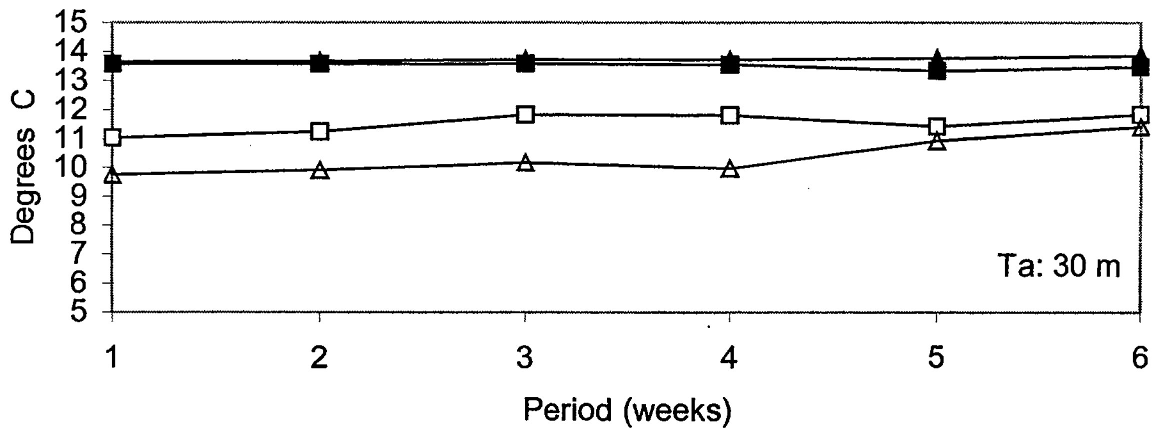
Period (weeks)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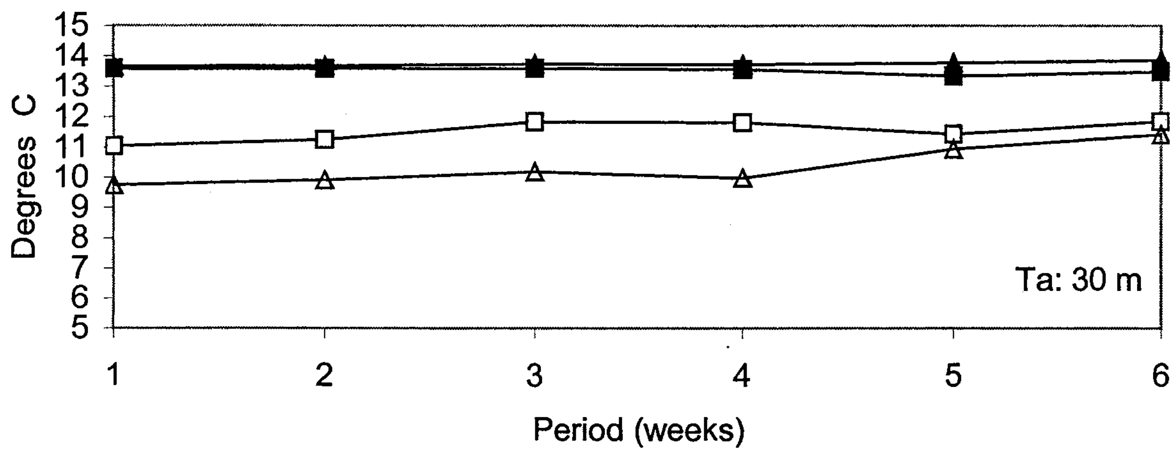
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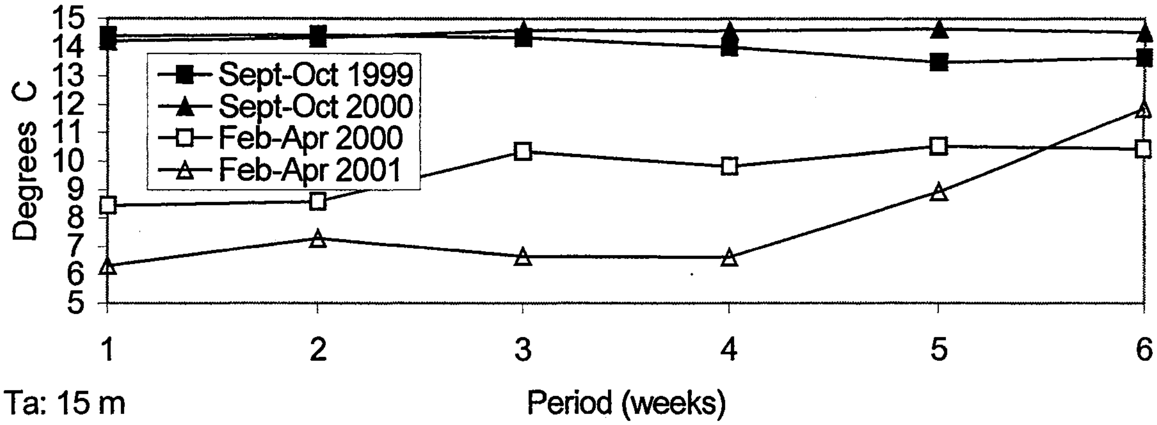
Period (weeks)

Figure 5. Substrate (rock) temperature from cave OK-220 in Adair County, Oklahoma, in September-October 1999 and February-April 2000 while natural airflow into the cave was obstructed by a solid iron door. Subsequent observations were made in September-October 2000 and February-April 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 (one week).



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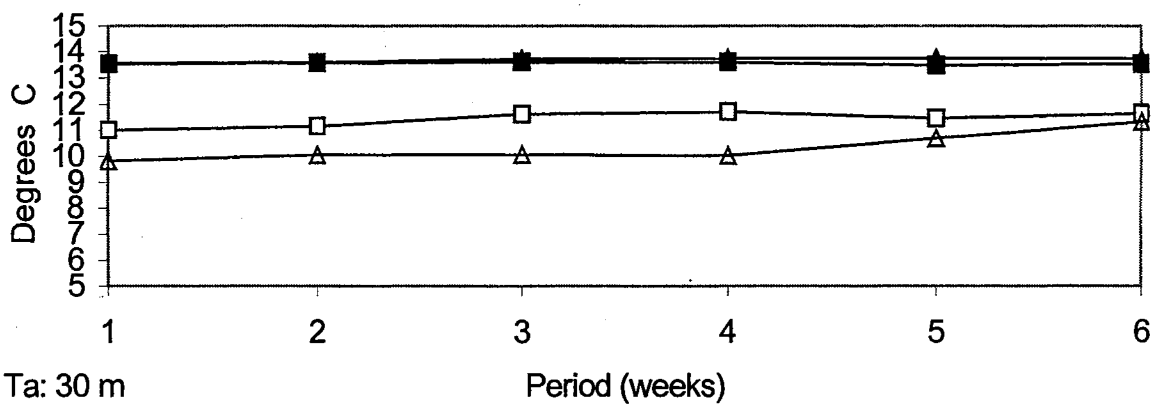

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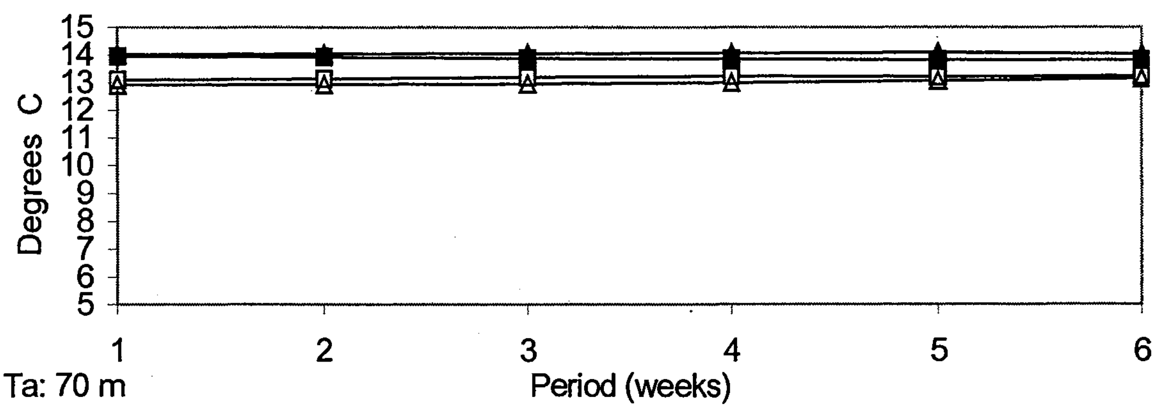

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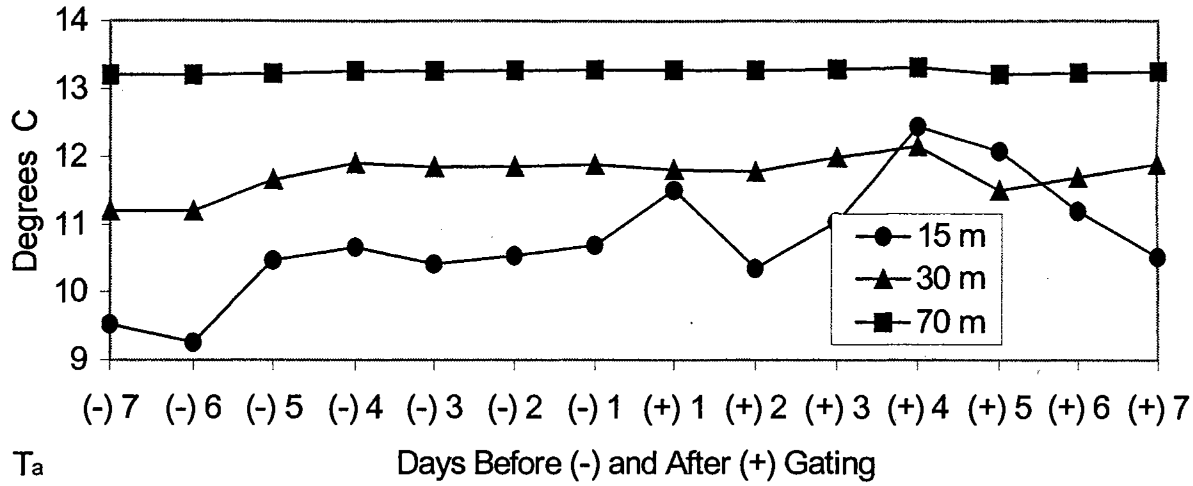

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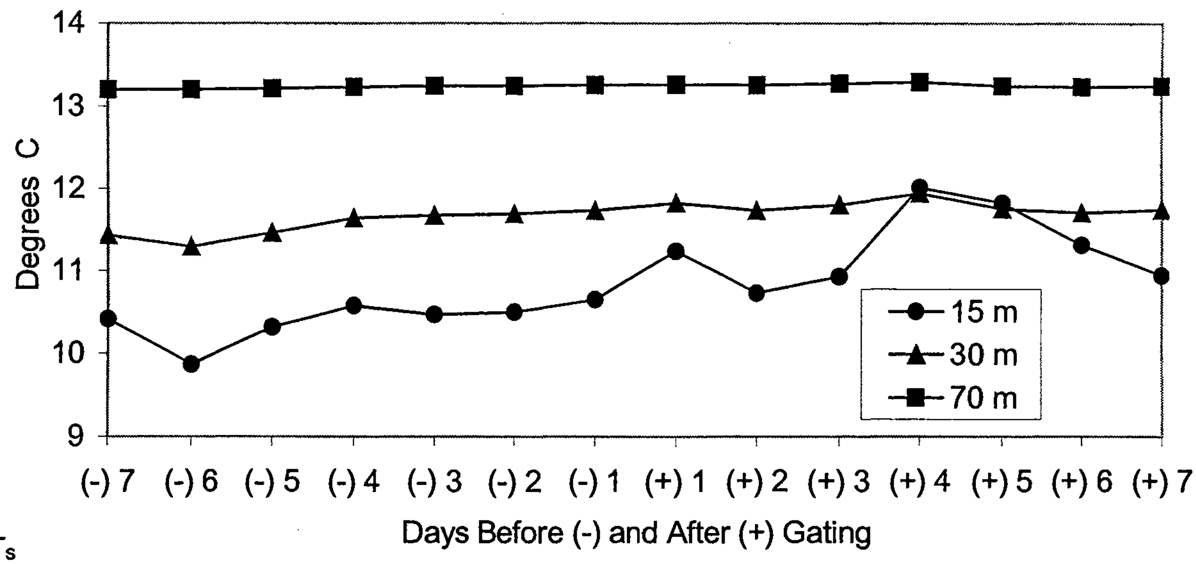
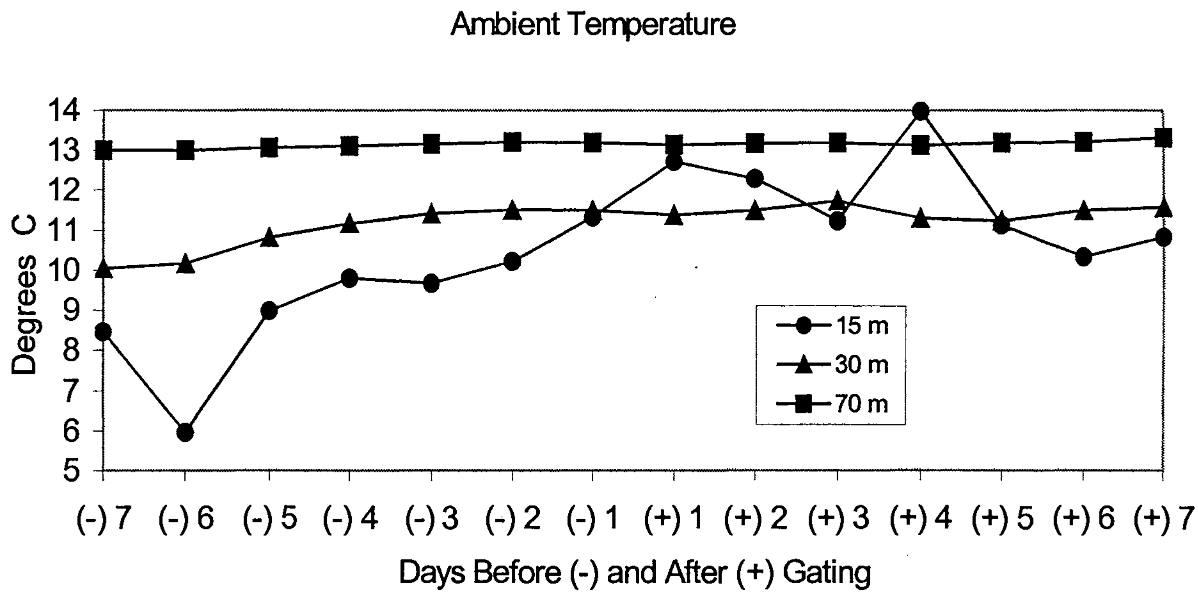


Ts

Figure 6. Ambient (T_a) and substrate (T_s) temperatures at cave OK-220 in Adair County, Oklahoma. Observations were made 7 days before and 7 days after an iron door covering the cave entrance was removed allowing natural airflow to resume. Each data point represents a mean of 48 observations recorded every 30 minutes for a 24-hour period.



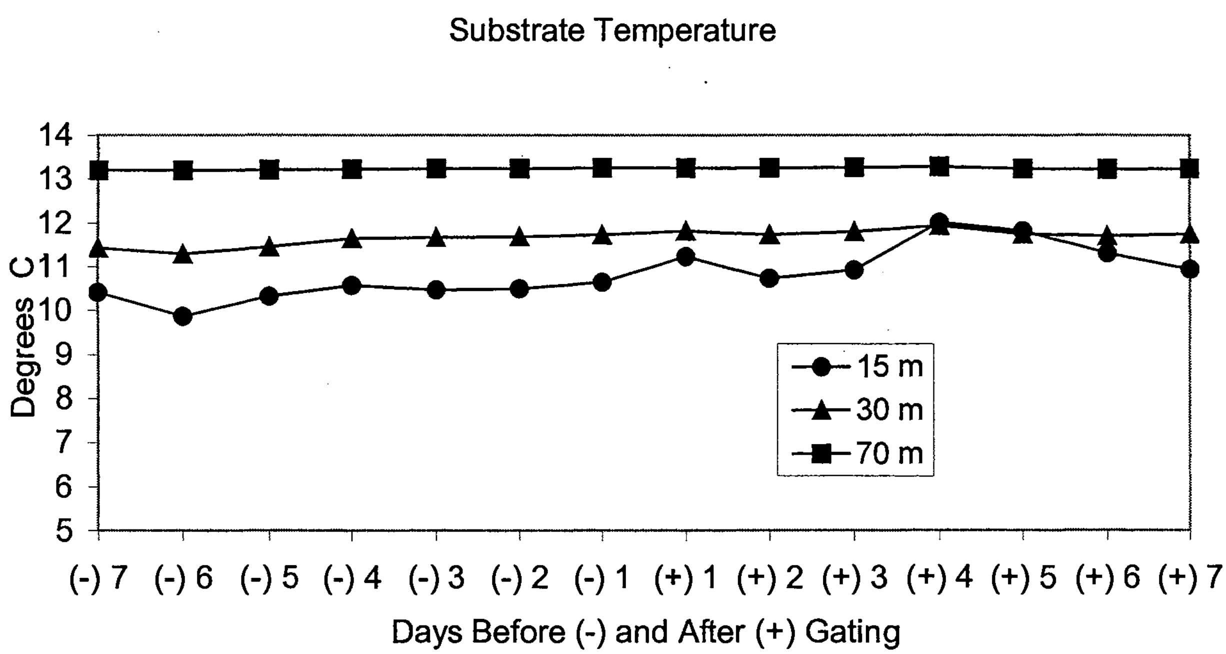


Figure 7. Ambient and substrate temperatures at cave OK-220 in Adair County, Oklahoma. Observations were made 7 days before and 7 days after an internal gate system was installed 7 m inside the cave entrance. Each data point represents a mean of 48 observations recorded every 30 minutes for a 24-hour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

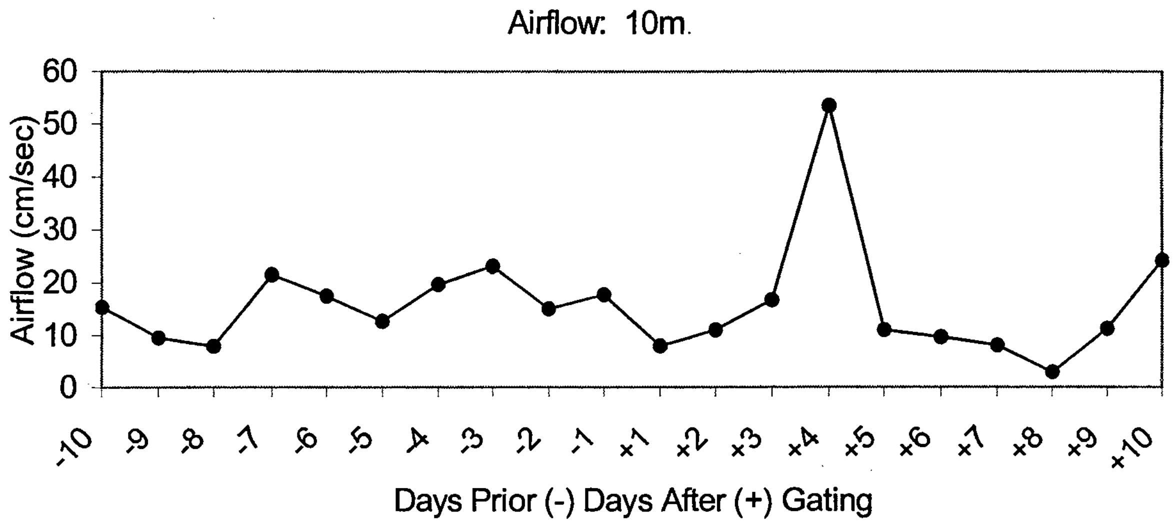


Figure 8. Airflow rates at cave OK-220 in Adair County, Oklahoma. Observations were made 7 days before and 7 days after an internal gate system was installed 7 m inside the cave entrance. Each data point represents a mean of 48 observations recorded every 30 minutes for a 24-hour period.

CHAPTER III

EFFECTS OF PASSAGE MANIPULATIONS ON CAVE CLIMATE

Abstract

Efforts intended to eliminate disturbance resulting from human entry to caves inhabited by bats typically is accomplished by construction of gates at cave entrances. However, a systematic assessment of the impacts on climate of cave interiors by the installation of internal gate systems in cave passages is conspicuously missing. The intent of this study was to compare winter climate variables in two caves before and after airflow was intentionally modified within each cave's passage. Modification of natural airflow in cave passages may affect internal climate. Ultimately, modifications to airflow can affect life-history characteristics of bats such as metabolic rates, fetal and neonatal development, and thermoregulation. In Cave OK-8 no differences occurred in ambient (air) or substrate (rock) temperatures inside the passage of after airflow was obstructed. A difference occurred only in relative humidity at 8 m inside the cave passage. In Cave OK-9 ambient and substrate temperatures differed at 42 m but not at 21 m or 60 m after natural airflow was obstructed. Relative humidity at 42 m inside cave OK-9 did not differ after modifications to the cave passage. Data presented here can provide an understanding of how management efforts to protect cave-dwelling bats that involve modifications to cave passages, can affect climate of cave interiors.

Introduction

Persistent or casual human disturbance at maternity caves and hibernacula has been implicated as a major cause for the decline in populations of most cave-dwelling bats (Barbour and Davis 1969; Humphrey and Kunz 1976; Tuttle 1979; American Society Mammalogists 1992). Conservation efforts that concentrate on protecting these caves and the colonies of bats that they harbor are possibly the most important contemporary issues in bat conservation in the United States (American Society of Mammalogists 1992). These efforts are usually intended to eliminate disturbance resulting from human entry to these caves. Protection typically is accomplished by construction of gates at cave entrances, fencing of cave entrances, placement of warning signs at entrances, and maintaining a close and positive rapport with private landowners.

Twenty-four entrances to caves in northeastern Oklahoma are presently protected with internal gates. Seven of those caves have been inhabited historically by colonies of gray bats. Thirteen entrances to caves inhabited by populations of Ozark big-eared bats (*Corynorhinus townsendii ingens*), big brown bats (*Eptesicus fuscus*), eastern pipistrelles (*Pipistrellus subflavus*), northern bats (*Myotis septentrionalis*), and a single hibernaculum of Indiana bats (*Myotis sodalis*) are similarly protected. Additionally, four caves that contain populations of Ozark blind cavefish (*Amblyopsis rosae*) and the Ozark blind crayfish (*Cambarus* sp.) also are protected from human entry by internal gates.

Although internal placement of gates within "dark zones" of cave passages may be the most effective method to deter human access to critical bat roosts, their effects on resident bats and microclimate of cave interiors have not been measured completely (Tuttle 1977; Tuttle and Stevenson 1977; Humphrey 1978; White and Seginak 1987; Richter et al. 1993). It is suspected by some researchers that cave gates alter airflow in cave passages (Humphrey 1978; Richter et al. 1993; U.S. Fish and Wildlife Service 1984).

Recently, there have been concerted efforts by biologists to analyze ambient and physical characteristics of bat roosts for various species (Raesly and Gates 1987; Hamilton and Barcley 1993; Lacki et al. 1993, 1994; Clark et al. 1996; Hurst and Lacki 1999; Waldien 2000). Natural characteristics of cave entrances affect internal ambient conditions, such as number of entrances, size of entrances, passage size, presence of water flow, air flow, and annual range of temperatures outside the cave (Tuttle and Stevenson 1977). Designed experiments and quantitative data on effects of modifications to cave entrances on internal cave microclimates, such as cave gates, are limited to nonexistent. Richter et al. (1993) reported degradation of winter habitat for hibernating populations of Indiana bats at caves where entrance modifications had occurred. Although those modifications did not involve gate systems, they illustrated how anthropogenic alterations to cave entrances can effect cave microclimates, and ultimately fat storage in hibernating Indiana bats.

The intent of this study was to compare winter abiotic (ambient temperature, substrate temperature, relative humidity, dew point, and airflow) variables in two caves before and after airflow was intentionally modified at each cave's entrance. Altered airflow should cause changes in some microclimate variables, especially at monitoring distances close to the cave entrances.

Results from these data can assist in measuring effects of entrance and passage modifications such as internal cave gates, on internal cave climatic conditions.

Materials and Methods

In winter 2001, climate variables were monitored in passages of two caves before and after modifications to each cave passage occurred. An internal gate was constructed 6 m inside the entrance of cave OK-8 in 1983. There are two entrances to this cave, with passage areas of 0.75 m^2 and 6.5 m^2. Internal gate systems were installed within the passages of each. As is typical of all gate systems installed within caves in Oklahoma, 4" angle-iron spaced 6¼" apart make up bars dissected the cave passage horizontally. This spacing allows for bats to fly though an internal gate system, effectively prevents human entry into the cave, and seems to allow ample airflow to a cave's interior as indicated by anemometer measurements (Table 1). A summer population of about 8,000 female gray bats have consistently used this cave in Adair County, Oklahoma (Martin et al. 2000). A small population of eastern pipistrelles (<200) and typically 1-2 gray bats use the cave as a winter hibernaculum.

Likewise, an internal gate system was installed 17 m inside the entrance to cave OK-9 located in Cherokee County, Oklahoma, in 1991. A summer population of >20,000 female gray bats annually use this cave, but only a small population (<20) of eastern pipistrelles use the cave as a hibernaculum in winter (Martin et al. 2000).

Climate variables (ambient temperature, substrate temperature, dew point, relative humidity, and airflow) were monitored at specific distances within each cave's passage for 7 consecutive days in January-February 2001. Subsequent variables were again monitored for 7 consecutive days after a solid section of corrugated cardboard was attached to the internal gate system to obstruct airflow into the cave. It is not unusual for hibernating bats to exit caves on warm days during hibernation, so a 20-cm section near the cave ceiling was left open for that reason.

Climatic variables were measured using HOBO H8 continuous data loggers (Onset Computer Corporation, Bourne, Maine). Three groups of data loggers were placed at specific distances of 8 m, 60 m, and 96 m inside cave OK-8 and 21 m, 42 m, and 60 m inside the entrance to cave OK-9. Four of the six groups of data loggers coincided with historical locations of bat roost sites. One logger at each station collected ambient temperature, relative humidity, and dew-point temperature. A second data logger monitored substrate temperature using an external probe placed in a hole drilled 1 cm into the rock substrate. Data loggers were attached together and suspended within 25 cm of the cave ceiling. If the cave ceiling could not be reached, data loggers were suspended from a rock ledge about 1.5 m from the cave floor.

Airflow was monitored using a sonic anemometer (Handar Instruments, Sunnyvale, California) placed 8 m inside the entrance to cave OK-8 and 22 m inside the entrance to cave OK-9. As is typical of most caves in Oklahoma, these caves tend to breath "inwardly" during winter. Measurements of airflow were collected 2 m inside the internal gate after airflow passed through the system.

Ambient conditions were recorded every 30 minutes during the 14-day period. For statistical comparisons, recordings were combined into means consisting of 24 observations, each mean representing a 12-hour period from cave OK-8 (Table 1) and OK-9 (Table 2). A randomized-complete-block ANOVA (SAS Institute Inc. 1999) compared open-passage and obstructed-passage variables inside each cave. Each 12-hour period of observation served as a block. Main units were open/obstructed airflow and data logger distances.

Results

Cave OK-8

There were no effects on ambient (air) cave temperatures by obstructing airflow (F = <0.01, df = 1,13; P = 0.95). There was an effect of distances inside the cave entrance where ambient temperatures were collected. Each variable mean was compared between the same monitoring distances before and after inward airflow was obstructed. No differences occurred in ambient temperatures at any distance (8 m: F = 0.10, df = 1,50.6, P = 0.76; 60 m: F = 0.00, df = 1,50.6, P = 0.96; 96 m: F = 0.16, df = 1,50.6; P = 0.69; Fig.1). Interaction did occur between open/obstructed airflow and distance for substrate temperatures. These temperatures differed 8 m inside the cave entrance (F = 63.58, df = 1,77.9; P = <0.0001), but not at 60 m (F = 0.07, df = 1,77.9, P = 0.80) or 96 m (F = 0.17, df = 1,77.9, P = 0.68; Fig. 2). Relative humidity means before and after airflow was obstructed did not differ (F = 3.01, df = 1,26; P = 0.09) at 8 m inside cave OK-8 (Fig. 3).

Cave OK-9

There were no effects on ambient (F = 0.62, df = 1,26; P = 0.44) or substrate (F = 0.00, df = 1,78; P = 0.95) temperatures by obstructing airflow in cave OK-220. There was interaction between open/obstructed airflow and monitoring distances and an effect of distances inside the cave entrance. Ambient temperatures of natural and obstructed airflow conditions in cave OK-9 differed at 42 m (F = 4.76, df = 1,59.2; P = 0.03) but not at 21 m (F = 0.81, df = 1,59.2; P = 0.37) or 60 m (F = 1.57, df = 1,59.2, P = 0.22; Fig. 4). Substrate temperatures differed at 21 m (F = 8.07, df = 178; P = 0.01) but not at 42 m (F = 0.65, df = 1,78; P = 0.42) or 60 m (F = 3.71, df = 1,78, P = 0.06; Fig. 5). Relative humidity at 42 m inside cave OK-9 did not differ (F = 0.05, df = 1,26; P = 0.82) before and after modifications to the cave passage (Fig. 6).

Discussion

Effects that natural external climatic factors such as temperature, atmospheric pressure, and airflow have on internal ambient cave environments are well documented in literature (Tuttle and Stevenson 1977; Richter et al. 1993). Although airflow is influenced directly by changes in temperature and atmospheric pressure, it may be the most influential factor in dictating ambient conditions inside caves. Tuttle and Stevenson (1977) discussed more important effects of cave structure and elevational displacement of internal air volume on ambient cave conditions. From a biological standpoint, these factors combine to create habitats that correlate to high evolutionary specialization typically exhibited by obligate cave fauna. Peck (1998) noted $\geq$ 1,353 (425 aquatic, 928 terrestrial) animal species that were restricted to subterranean habitats in the U.S. and Canada. In roost restrictive, obligate cave-dwelling species such as the gray bat, fewer than 5% of available caves are suitable for occupation (U.S. Fish and Wildlife 1982). 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. Poor thermoregulation in these bats may result in slow maturation, thus reducing survival and natality (Studier and O'Farrell 1972; Humphrey 1975). Availabilities of optimal microclimates for roost sites during winter hibernation and summer maternity seasons are critical. It is therefore likely that distribution of caves containing appropriate internal ambient conditions plays an important role in distribution and ranges of cave-dwelling bat species (Tutttle and Stevenson 1977; Raesley and Gates 1987; Thomas 1995).

The scope of this study was to analyze effects that anthropogenic modifications of cave entrances and passages have on movement of air into and out of a cave and ultimately internal climatic conditions. As do most caves in eastern Oklahoma, caves OK-8 and OK-9 tend to breath "inwardly" in winter months, when external air is cooler than internal cave temperatures. Effects of impeded airflow by passage modifications should be magnified in these months when external airflow is carried into the cave's interior.

Of all variables measured, only relative humidity at a distance of 8 m was affected by modification to the passage in cave OK-8. In this experiment, only airflow through the larger of the two passages was obstructed. Airflow through the smaller, second entrance may have compensated for a lack of airflow through the larger passage located only 10 m away, creating a lack of significant differences in ambient and substrate temperatures located farther into the cave passage.

Two locations monitoring ambient conditions in the passage of cave OK-9 differed in ambient (42 m) and substrate (21 m) temperatures between open and obstructed observations. This cave had a single entrance with a relatively small passage of < 3 m^2. Recordings of air movement before the passage was obstructed indicated relatively small increments of air entered the cave in winter (Table 2), even under natural airflow conditions. Remarkably, differences between minimum and maximum daily means during the entire 14-day monitoring period were only 1.28°C for substrate temperatures at 21 m and 0.95°C for ambient temperatures at 42 m. However, those differences indicated statistical significance. For comparison, differences between minimum and maximum daily means during the 14-day period at 60 m inside the cave passage were 0.10°C for ambient and 0.11°C for substrate temperatures and were not significantly different. Although these changes between open and obstructed airflow conditions represent statistical significance, they do indicate how difficult it is to obtain nonsignificant statistical test effects from values that present such small variations, such as those found in cave environments.

An obvious gradient in maximum/minimum ranges in climatic variables exists in cave environments, being greater in the ecotonal environment near the entrance and narrowing as passage length reaches 50-60 m and beyond. Passage size, entrance size, entrance orientation (vertical vs horizontal), number of entrances, and passage to entrance elevational configurations determine rate of airflow into and out of a cave ecosystem. Ultimately these characteristics influence internal climatic conditions and decrease the gradient in ranges between minimum and maximum values for climatic variables as passage length increases. These climatic characteristics are influenced by large volumes of air movement in some caves, but lesser volumes in others. It is apparent from these data that caves exhibiting what might be considered moderate to low volumes of airflow, indicate no changes, or only slight changes in relative humidity, ambient temperatures, and substrate temperatures, when airflow is essentially removed. It may be appropriate to assume, therefore, that appropriately placed internal gate systems that allow ample airflow (Table 1) also would have minimal effects on internal ambient cave conditions.

Caves OK-8 and OK-9 exhibit rather typical characteristics of most caves in Oklahoma that have internally gated passages. Relatively small colony sizes (<30,000) of resident bat populations, relatively small gated passages conducive to lower volumes of airflow, and internal positioning of gate structures in "dark zones" of cave passages probably contribute to the apparent acceptance of full passage gates by resident bat populations in eastern Oklahoma. This is further substantiated by the presence of bat colonies exhibiting stable populations, including in caves OK-8 and OK-9, using caves in eastern Oklahoma that have manipulated passages and entrances (Martin et al. 2000).

Based on data from these experiments, it is recommended that current designs for internal gates that are appropriately placed and allow persistent airflow within a cave passage be considered as a viable management option. This is particularly when casual or persistent human disturbance is of primary concern when developing management plans for protecting vulnerable maternity and hibernating colonies of bats.

Acknowledgments

Many individuals, private landowners, and organizations have provided assistance in gathering data, gate construction, and have contributed time, resources and efforts to protecting the endemic bat species of Oklahoma. We would like to thank in particular the Tulsa Regional Grotto of the National Speleological Society and the Tulsa Nature Conservancy. Financial support was provided by the Federal Aid, Endangered Species Act under Project E-9 of the Oklahoma Department of Wildlife Conservation, Rogers State University, Oklahoma State University, and the Oklahoma Cooperative Fish and Wildlife Research Unit (Oklahoma State University, Oklahoma Department of Wildlife Conservation, U.S.G.S. Biological Resources Division, Wildlife Management Institute cooperating).

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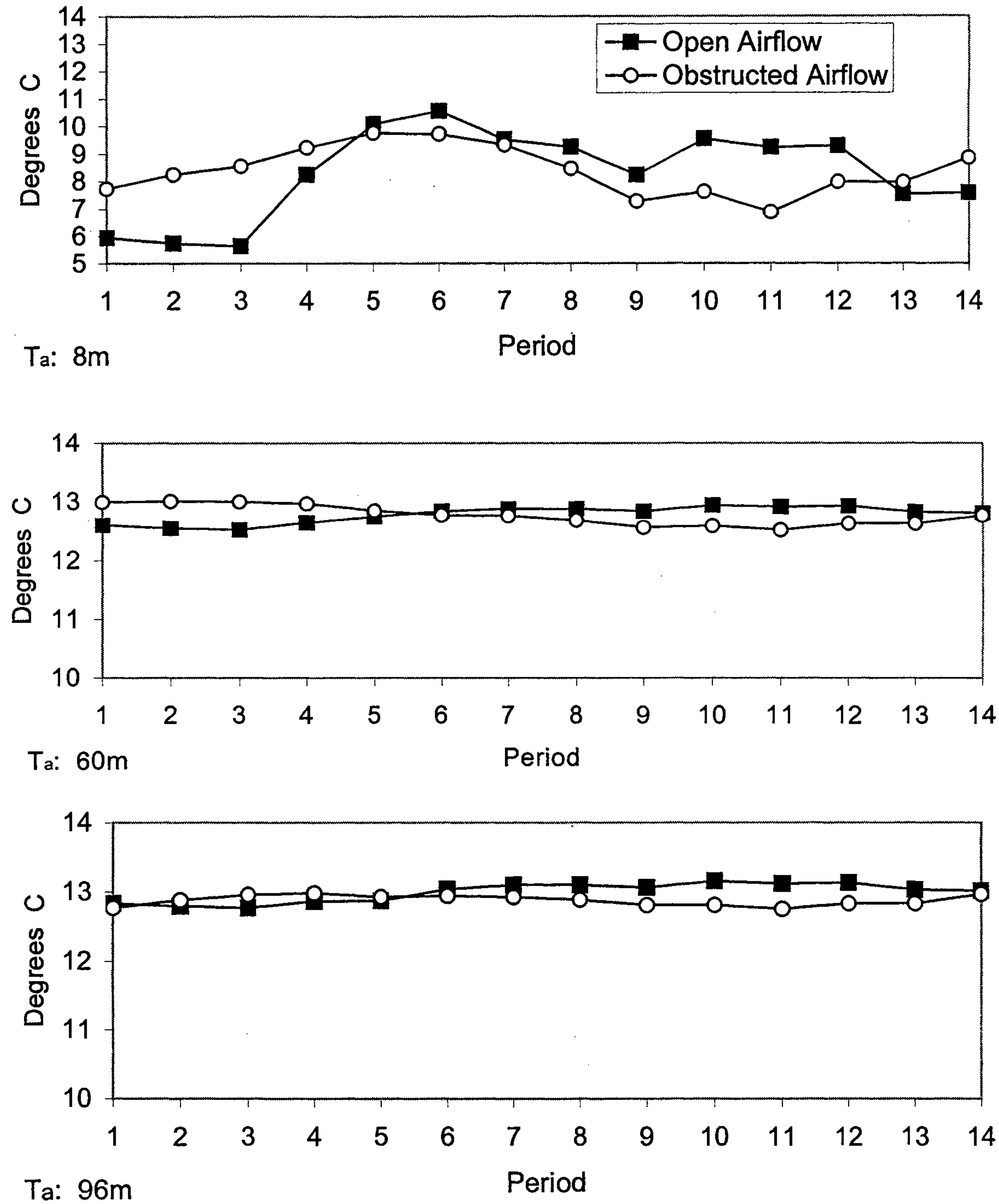
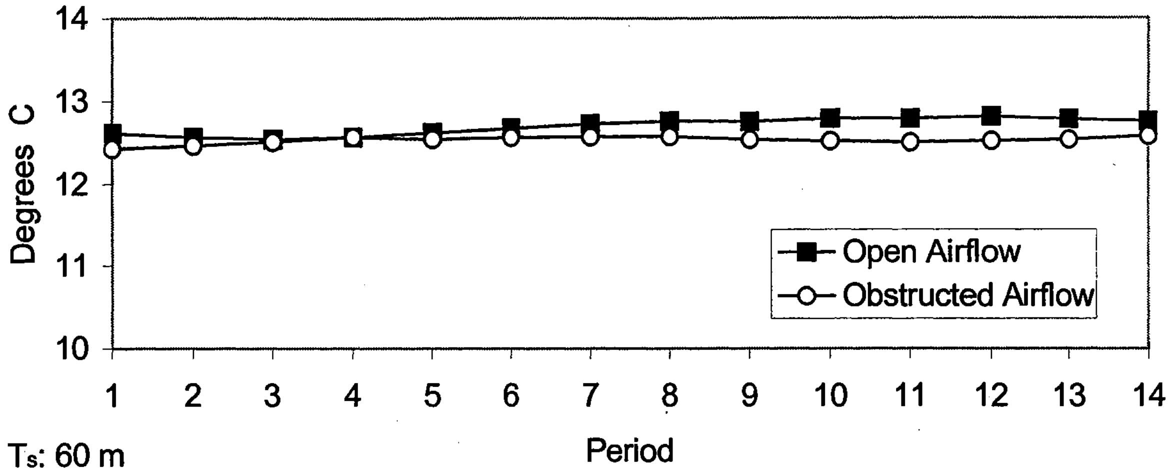
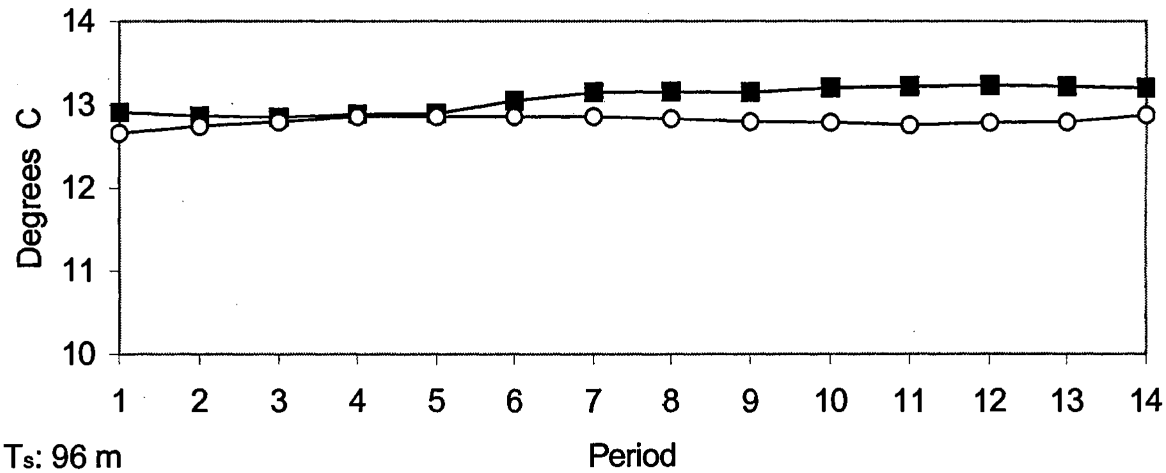


Figure 1. Ambient temperature at three distances inside cave OK-8 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with open airflow and 7 consecutive days with obstructed airflow. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.



Ts: 60 m



Ts: 96 m

Figure 2. Substrate temperature means collected at two distances inside cave OK-8 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with open airflow and 7 consecutive days with obstructed airflow. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.

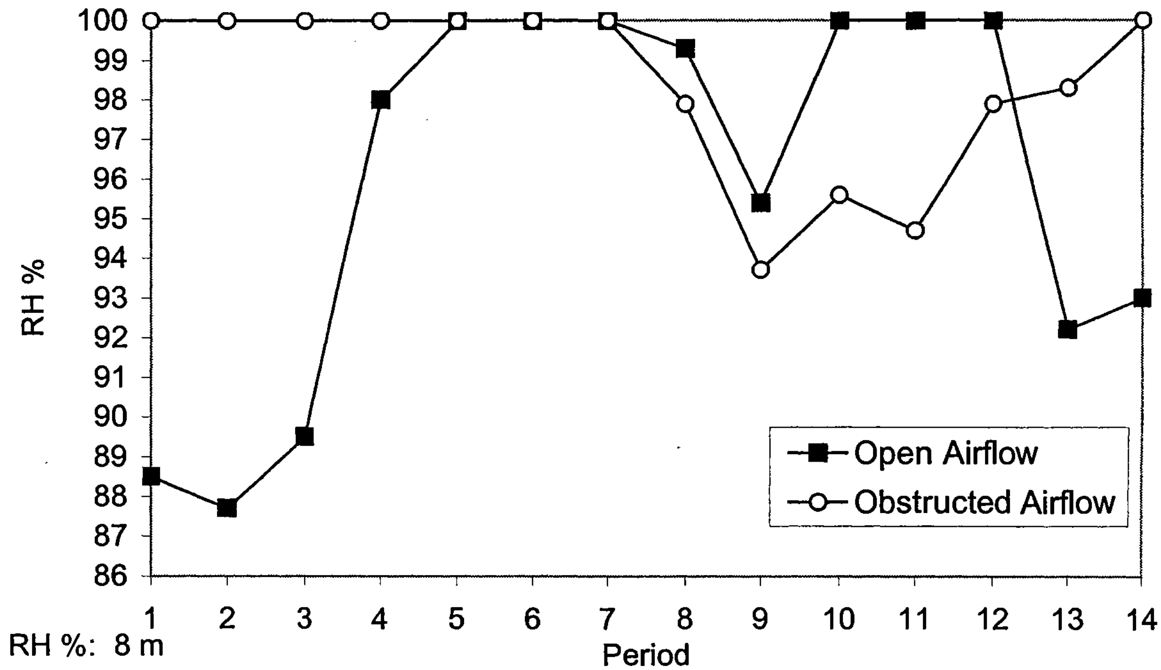


Figure 3. Recordings of relative humidity at 8 m inside cave OK-8 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with unimpeded airflow and for 7 consecutive days with airflow reduced to 0.0 m/sec. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.

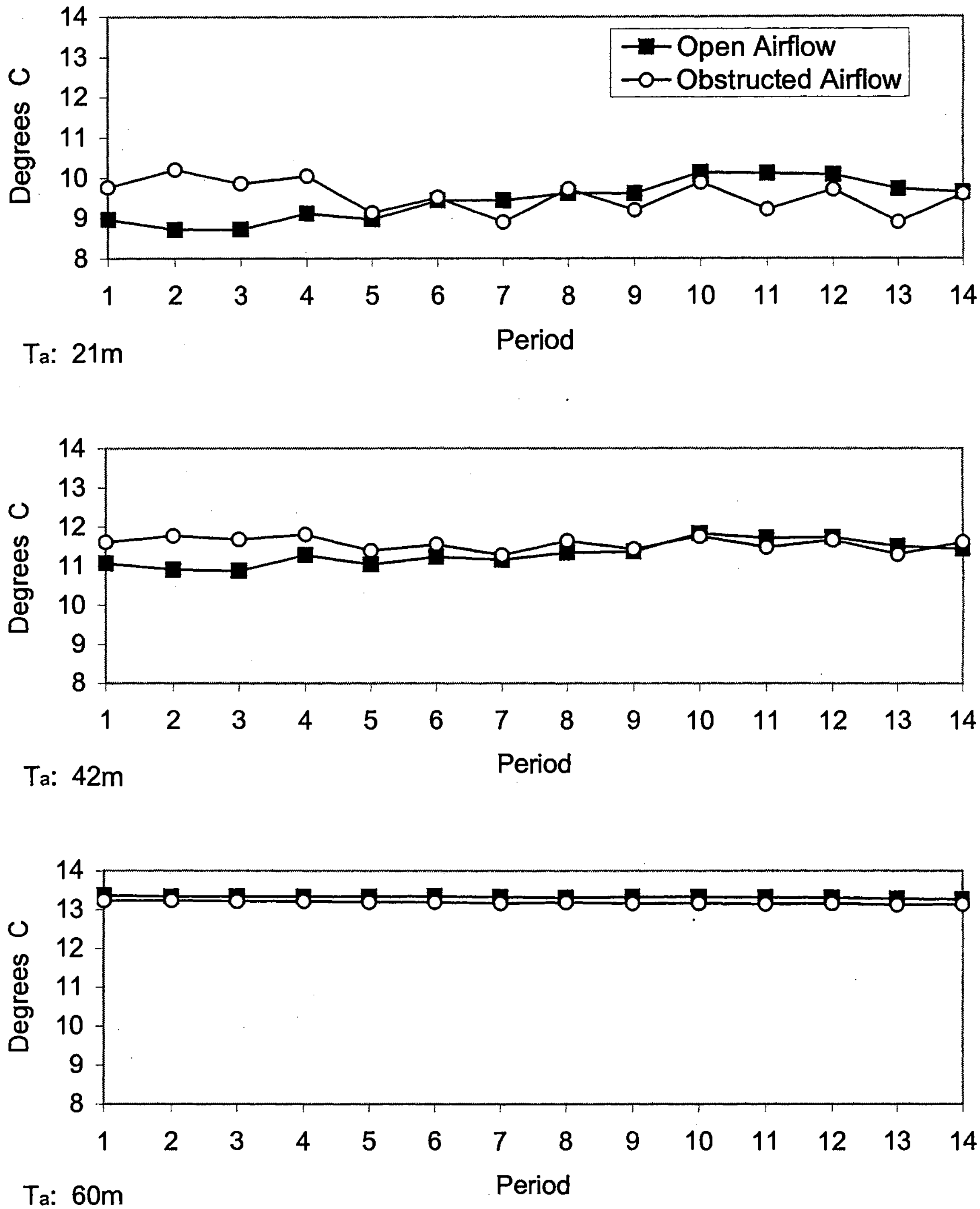


Figure 4. Ambient temperature at three distances inside cave OK-9 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with open airflow and 7 consecutive days with obstructed airflow. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.

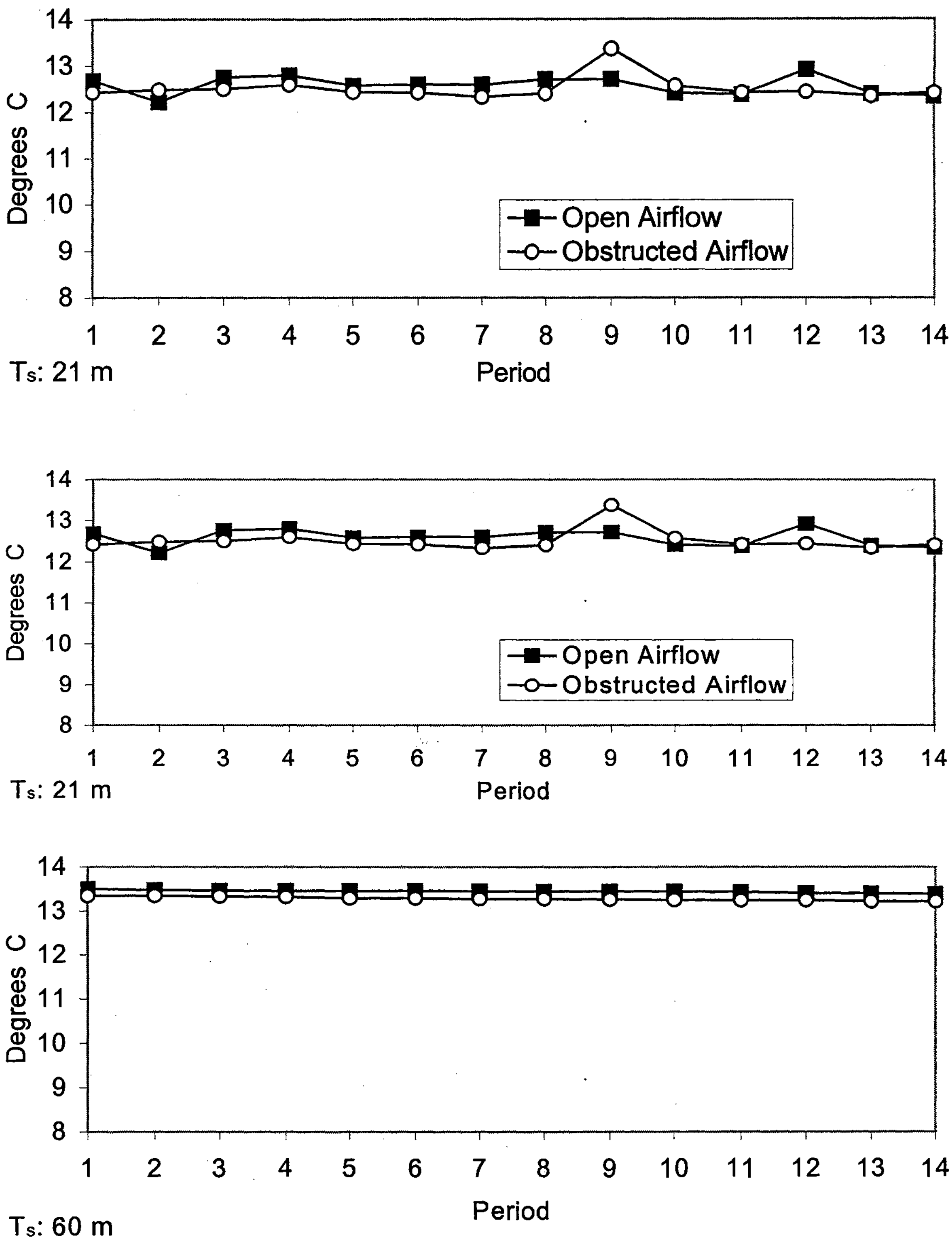


Figure 5. Substrate temperature three distances inside cave OK-9 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with open airflow and 7 consecutive days with obstructed airflow. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.

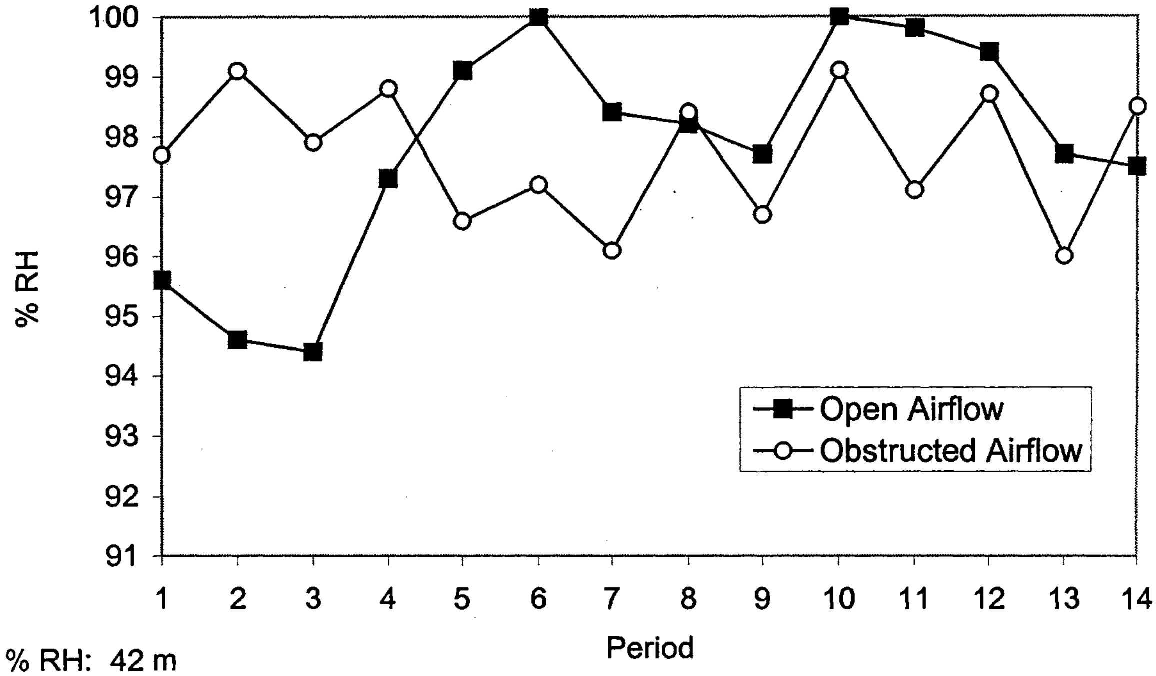


Figure 6. Relative humidity means collected at a distance of 42 m inside cave OK-9 in northeastern Oklahoma. Observations were recorded for 7 consecutive days with open airflow and 7 consecutive days with obstructed airflow. Each data point represents a mean of 24 observations recorded every 30 minutes for 12 hours.

CHAPTER IV

MANAGEMENT RECOMMENDATIONS FOR USING INTERNAL CAVE GATES FOR PROTECTING CAVE-DWELLING POPULATIONS OF BATS

Cave biologists often are faced with declines in populations of cave-dwelling species of bats. We find ourselves engaged in an unenviable predicament between aggressive protection and management of critical subterranean habitats and possibly altering that habitat to the extent that resident populations of fauna will no longer use it. Unlike most terrestrial habitats, caves are essentially nonrenewable. We are still endeavoring to understand completely how subtle changes in airflow, hydrology, and nutrient input from the surface can affect faunal populations in caves. We do know that about 18 species of bats found in North America rely substantially on caves throughout the year, and 13 use caves year-round. Additionally, all North American bats listed as endangered or threatened by the U.S. Fish and Wildlife Service are obligate cave-dwelling species or subspecies (McCracken 1989; Harvey et al. 1999; Pierson 1999). Persistent or casual human disturbance at critical caves such as maternity caves and hibernacula can be implicated as a major cause for declines in populations of most cave-dwelling bats (Barbour and Davis 1969; Humphrey and Kunz 1976; Tuttle 1979; American Society Mammalogists 1992).

In most cases, passive management efforts such as good landowner relations, fencing around cave entrances, placing warning signs against trespassing at entrances, and three-quarter passage gates may not offer adequate protection to resident bat populations that are declining. Considerable thought and apprehension should be given before manipulating a cave entrance or passage to protect resident fauna. It is particularly evident that external cave gates can be restrictive to exiting bat colonies and have resulted in colony abandonment (Ludlow and Gore 2000; Martin et al. 2000). However, data presented here show that appropriately placed internal gates in cave passages can protect bat populations with minimal effects on cave microclimates and exit flights by bats.

Cave biologists in Oklahoma have videotaped exit flights of gray bats through internally gated passages with no noticeable effect on bat flight. Observations of exit flights from gated caves (n = 36) did not differ from those at open-passage caves. There have been recurrent claims in literature that internal gates increase 1) swarming behavior by bats, 2) susceptibility to predation, and 3) increased propensity to drop young as a result of swarming (Tuttle 1977; 1979; White and Seginak 1987; Ludlow and Gore 2000). These concerns were not supported by data or anecdotal observations presented here.

Two temperature parameters (ambient and substrate means and ranges) were measured at three distances in 8 caves under gated and open-passage conditions. These recordings resulted in 48 observational sessions under warm-season (August-October) and 48 observational sessions under cold-season (December-March) conditions. Only a single significant difference was found in warm-season temperature means between gated and open-passage caves. These data indicate that there is little or no effect on cave temperatures (ambient and substrate means or ranges) by internal placement of gates in cave passages during warm seasons.

Temperature means and ranges measured under cold-season conditions did not differ when comparing gated and open-passage caves (Chapter I). Some cold-season ambient and substrate temperature means differed in two caves immediately before and after manipulation to their respective passages; however, ranges in ambient and substrate temperatures did not differ under the same passage treatments (Chapter II). In the same experiment, variation in maximum temperature means compared at any distance inside cave OK-13 in winter 2000 during open-passage conditions and winter 2001 during gated conditions was 1.13°C. The widest variation in maximum temperature means compared at any distance inside cave OK-220 in winter 2000 during obstructed conditions and winter 2001 during open-passage conditions was 3.70°C. Although statistically significant, the biological importance of such narrow variation on resident cave fauna is debatable.

These conclusions are further supported by the presence of stable populations of bats in all caves in Oklahoma with passages that are protected with internal gate systems. Listed below are several physical and ecological characteristics of caves in Oklahoma that are protected with internal gate systems:

- All internal gates are located in twilight or dark zones of cave passages at distances of 3-17 m from their respective entrances.
- Passage areas where gates are located are relatively small and range from 1.38 – 6.5 m^2.
- Colony sizes of gray bats (7,000 – 30,000), Ozark big-eared bats (<45), and eastern pipistrelles (<200) are relatively small.

- Five caves that have internal gate systems are inhabited by gray bat maternity colonies; the largest has a stable population of 30,000 individuals.
- Three caves where airflow was measured indicate low to moderate rates of airflow from 1.49 to 17.7 cm/sec.
- In four instances, multiple passages are gated in the same cave. In one instance, there are 6 passages gated within the same cave system.
- All internal gate systems in caves in Oklahoma are full-passage gates offering optimum protection against human entry and disturbance.

Data presented may not be completely definitive. It is hoped that the stigma and rhetoric that is typically associated with cave gating will give way to broader investigations into effects that internal gate systems have on cave climatic conditions and ultimately resident bat populations. A greater understanding of these effects will lead to sound management efforts that can eliminate one factor, human disturbance, contributing to the decline of cave-dwelling populations of bats.

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