BASELINE POPULATION ESTIMATES AND MICROCLIMATE DATA FOR NEWLY ESTABLISHED OVERWINTERING BRAZILIAN FREE-TAILED BAT COLONIES IN CENTRAL TEXAS

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ABSTRACT—Behavioral changes of migratory species have been globally documented in recent decades. However, there is a paucity of research on changes in migratory bat species. Brazilian free-tailed bats (*Tadarida brasiliensis*) roost in central Texas from March to November. These bats have historically migrated south in late fall, leaving summer roosts unoccupied during winter. Recently, overwintering populations have been discovered in central Texas. The objectives of our study were to determine presence or absence of overwintering free-tailed bats at six known summer roosts, obtain baseline population estimates, and evaluate microclimates of roosts during winters of 2010–2011 and 2011–2012. We used data loggers to monitor temperature and humidity hourly. We estimated population sizes with digital images using ImageJ software, previously established roosting densities, or both. Our results indicated that occupied roosts were colder, had less stable temperatures, and had a stronger correlation between internal and external temperatures vs. unoccupied roosts. Population sizes increased at all occupied roosts from 2010 to 2011.

RESUMEN—Los cambios de comportamiento de las especies migratorias se han documentado a nivel mundial en las últimas décadas. Sin embargo, hay una escasez de investigación sobre los cambios en las especies de murciélagos migratorios. Los murciélagos cola suelta brasileños (*Tadarida brasiliensis*) forman dormideros en el centro de Texas desde marzo a noviembre. Históricamente estos murciélagos han emigrado al sur a fines de otoño, dejando dormideros estivales desocupados durante el invierno. Recientemente, las poblaciones invernales se han descubierto en el centro de Texas. Los objetivos de nuestro estudio fueron determinar la presencia o ausencia de los murciélagos de cola suelta brasileños durante el invierno en seis dormideros estivales conocidos, obtener estimaciones del tamaño poblacional como referencia, y evaluar los microclimas de los dormideros durante los inviernos de 2010–2011 y 2011–2012. Utilizamos registradores de datos para monitorear la temperatura y la humedad cada hora. Estimamos los tamaños poblacionales con imágenes digitales usando el software ImageJ, densidades de dormideros previamente medidos, o ambos. Nuestros resultados indicaron que los dormideros ocupados fueron más fríos, tuvieron temperaturas menos estables y tuvieron una correlación más fuerte entre temperaturas internas y externas en comparación con dormideros desocupados. Tamaños poblacionales aumentaron en todos los dormideros ocupados desde 2010 hasta 2011.

In connection with climate-change research, behavioral changes of migratory species, including timing of migration and range shifts, have been documented globally in recent decades (Roff, 2002; Parmesan and Yohe, 2003; Knudsen et al., 2011). Recognizing and studying these changes can contribute to management and conservation efforts for these species. For some animal groups, such as birds, phenology has been well studied (Gwinner, 1990; Berthold, 1993; McWilliams et al., 2004; Knudsen et al., 2011). However, there is a paucity of research on migratory bats despite an increased interest due to high mortality rates during migration at wind energy facilities (Kunz et al., 2007; Baerwald and Barclay, 2009; McGuire and Guglielmo, 2009; Wiederholt et al., 2013) and the spread of white-nose syndrome (WNS) across the nation (Blehert et al., 2009; Cohn, 2012). In fact, McGuire and Guglielmo (2009) suggested using bird migration research to predict and assess bat migration physiology because of a lack of bat data.

Brazilian free-tailed bats (*Tadarida brasiliensis*; hereafter free-tailed bat) inhabit caves, bridges, buildings, and abandoned mines and tunnels in central Texas from March to November (Wilkins, 1989). These populations have long been considered migratory, traveling to more southern latitudes during winter (Villa, 1956; Glass, 1958; Villa and Cockrum, 1962; Wilkins, 1989). Small populations of free-tailed bats also have been documented as overwintering in Texas for many years; however, few attempts were made to enumerate their size (Krutzsch and Sulkin, 1958; Spenrath and LaVal, 1973; Glass, 1982; Tuttle, 2003; Keeley and Keeley, 2004; Scales and Wilkins, 2007). Recent observations signaled the establishment of new overwintering populations at roosts in central Texas, with several believed to be increasing in size (F. Hutchins, Bat Conservation International, and S. Fulton, Bamberger Ranch, pers. comm.). Multiple factors might contribute to increased overwintering behavior, including but not limited to the presence of a previously unavailable food source, such as overwintering migratory moths (Vaughan, 1976; Westbrook, 2008), changes in roosting sites within the winter range (Tuttle, 1977; Kunz, 1982; Wiederholt et al., 2013), as well as global climate change (Scheel et al., 1996; Popa-Lisseanu and Voigt, 2009; Frick et al., 2010). Climate change has been suggested as a key factor influencing migratory behavior of birds (Bezzel and Jetz, 1995; Bradley et al., 1999; Pulido and Berthold, 2010) and might also influence migratory behavior of bats (Popa-Lisseanu and Voigt, 2009; Wiederholt et al., 2013).

Despite their economic importance as vital insectivores of major crop pests in the region (Lee and McCracken, 2002; Cleveland et al., 2006), minimal survey and environmental data have been collected on overwintering populations of free-tailed bats in central Texas. Recent research at Carlsbad Cavern verified an overwintering population in New Mexico (Geluso, 2008); however, no published studies specific to overwintering free-tailed bat populations in Texas exist. The objectives of our study were to a) confirm the presence or absence of overwintering (November–February) free-tailed bat colonies at known summer roosts, b) obtain baseline estimates of overwintering populations, and c) assess microclimates within occupied and unoccupied winter roost sites.

Materials and Methods—We sampled six summer roosts containing free-tailed bats in central Texas during winter (November, December, January, and February) 2010–2011 and 2011–2012. Four of these summer roosts (Bracken Bat Cave, Comal County, 29°41′13″N, 98°21′10″W; D'Hanis Bridge, Medina County, 29°19′35″N, 99°17′42″W; Old Tunnel State Park, Kendall County, 30°06′02″N, 98°49′15″W; and the Chiroptorium, a human-made bat cave located at the Selah, Bamberger Ranch Preserve, Blanco County, 30°11′14″N, 98°28′34″W) had overwintering bat populations. Two roosts (Davis Blowout Cave, Blanco County, 30°27′17″N, 98°34′07″W and James River Bat Cave, Mason County, 30°34′14″N, 99°19′59″W) did not have confirmed overwintering populations. We visited each roost once per month (total of eight visits per location during two winters). We did not use data from a seventh roost with a confirmed overwintering population, Frio Bat Cave (Uvalde County) because of guano mining disturbance and data logger problems.

Population Estimates—We estimated overwintering bat populations in December 2010 and 2011. We used different methods to estimate populations at each roost because of the structural diversity of roosting locations as well as roosting habits of bats. We used digital photography and a laser caliper with a setting of 15.2 cm (Meretsky et al., 2010) for roosting area estimates and population counts at Bracken Bat Cave and Old Tunnel State Park. We took digital images perpendicular to roosting clusters using a Canon EOS Rebel T2i with a 70–300 mm lens and a Canon Speedlite 430EX II flash. The laser caliper and camera were mounted on a metal plate with two bubble levels perpendicular to the camera lens axis. The complete assembly was stabilized on a tripod. We reviewed the quality of digital images as pictures were taken in the field. We reduced disturbance to roosting bats whenever possible by only using enough light from the laser caliper to identify outlines of clusters and focus our camera. We used ImageJ (National Institutes of Health, USA), a public domain software program, to analyze all photos and count bats (Abramoff et al., 2004).

At Bracken Bat Cave, we included an entire cluster of roosting bats in one image and used a laser caliper distance of 15.2 cm to set the scale in ImageJ. This allowed us to draw polygons around roosting clusters and determine surface area at a roosting site. We drew polygons 10 times in each photo and calculated an average of the resultant areas. However, bats roosted approximately 38 m from the cave floor during both seasons, which prevented us from obtaining the resolution necessary to count individual bats for density estimates. Current and historical calculated density estimates of Brazilian free-tailed bat populations using extrapolation are either 2,153 or 3,229 adult bats/m^2 (Constantine, 1967; J. Kennedy, in litt.). We conservatively estimated bat density at 2,153/m^2 and extrapolated to the area based on the average size of polygons.

Bats roosted much closer to the camera at Old Tunnel State Park, which allowed us to take photos of sufficient quality for magnification. We used ImageJ to magnify images and estimate bats/m^2. We created a square of 30.5 $\times$ 30.5 cm on the magnified images using the laser caliper distance as a reference. We counted each bat inside each square to obtain a roosting density on 20 photos for each winter. We then averaged the 20 counts to obtain a mean roosting density. We placed a digitized point on the nose of each bat as it was counted to eliminate double counting. The roosting surface covered by bats was too long to incorporate into a single photo or stitch together in a series of images. The bats also did not uniformly cover the entire area. To estimate roosting area, we calculated the mean width of the surface covered by roosting bats and multiplied this mean by the length of the tunnel occupied by bats. We used 29 pictures in 2010 and 30 pictures in 2011 taken at random points within the occupied roost area to determine the mean percentage of roosting area covered by bats. We multiplied the mean roosting area by the mean percent area covered and mean number of bats/m^2 to derive a final population estimate. We did not apply this density estimate to Bracken Bat Cave because of differences in roosting substrate.

Bats roosted inside crevices at D'Hanis Bridge. A range for free-tailed bats roosting in bridge crevices (431–538 bats/m^2) had previously been established (Mylea Bayless, Bat Conservation International, pers. comm.). We averaged the high and low estimates of this range and combined this average with crevice measurements, recorded to the nearest centimeter, and mea-

Table 1—Population estimates and 95% confidence intervals (CI) for *Tadarida brasiliensis* at four overwintering roosts in central Texas during December 2010 and 2011. N/A, not applicable.

	December 2010		December 2011	
Site	Estimate	95% CI	Estimate	95% CI
Bracken	15,233	14,010–16,456	88,334	86,102–90,565
Chiroptorium	635	N/A	885	N/A
D'Hanis Bridge	216,128	192,115–240,140	226,349	201,199–251,499
Old Tunnel	65,015	63,067–66,963	254,502	245,248–263,757

surements of occupied roosting space taken with a 100-m measuring tape.

Last, the Chiroptorium holds seven bat houses of varying sizes. Overwintering bats occupied only bat houses during both seasons. We measured dimensions of each bat house and took pictures of colonies inside to visually estimate the percentage of space occupied in each bat house. We then used the accepted measurement for bat houses of two bats/2.54 linear cm (Mylea Bayless, Bat Conservation International, pers. comm.) and applied this value to total linear centimeters occupied.

Microclimate Habitat Analysis—We placed three Hygrochron iButton data loggers (Maxim Dallas Semiconductor Corp., Dallas, TX) inside and one outside each roost to monitor microclimate data on the first visit to each location in November 2010. We positioned data loggers as close to roosting bats as possible (most within 1 m). We could not position data loggers in Bracken Bat Cave near roosting bats to obtain representative measurements of the roosting environment, and therefore, we eliminated this roost from microhabitat analysis. Each data logger recorded temperature and relative humidity at 60-min intervals during November–February. We converted relative humidity to absolute humidity (g/m^3) using the recorded temperature and relative humidity data (Vaisala, http://www.vaisala.com/Vaisala%20Documents/Application%20notes/Humidity_Conversion_Formulas_B210973EN-F.pdf). We used absolute humidity instead of relative humidity because absolute humidity is independent of temperature and a better measure of air moisture than relative humidity (Colloff, 2009; Hillman et al., 2009).

All research was approved by the Texas State University-San Marcos Institutional Animal Care and Use Committee (Protocol 1029-0909-24). Safety decontamination precautions and procedures were taken by all who entered roosting sites because of concern for WNS following U.S. Fish and Wildlife Service's WNS decontamination protocol, version 01.25.2011.

Statistical Analysis—We determined 95% confidence intervals for population estimates for each roost individually because of differences in methodologies. We calculated the 95% confidence intervals using standard deviation of area estimates for Bracken Bat Cave. We used standard deviation of the number of estimated bats/m^2 to calculate confidence intervals at Old Tunnel State Park. We did not determine confidence intervals for the Chiroptorium because bat house estimates were based on an assumed amount of space required for an individual bat. To our knowledge, no range of densities has been reported and no methods for determining bat house population estimates have been published.

Finally, we calculated the D'Hanis Bridge confidence intervals using the range of estimated bats/m^2 (Mylea Bayless, Bat Conservation International, pers. comm.). We analyzed mean weekly temperature and mean absolute humidity of roosts with and without overwintering bats and provided summary statistics. We also analyzed correlations between internal and external temperatures with Pearson's correlation coefficient. Statistical analyses were conducted using R statistical software program (R Development Core Team, 2006).

Results—Free-tailed bats occupied Bracken Bat Cave, the Chiroptorium, Old Tunnel State Park, and D'Hanis Bridge during November, December, January, and February 2010–2011 and 2011–2012. James River Bat Cave was unoccupied both years. Davis Blowout Cave was occupied only in February 2011 and 2012 by free-tailed bats. Also, Old Tunnel State Park population increased during November 2010 on the basis of roost observations made the week before our visit by the park superintendent (Nyta Brown, Texas Parks and Wildlife Department, pers. comm.). From this information we assumed free-tailed bat migration was in progress during November and February and therefore we restricted analyses to data from nonmigratory winter months of December and January.

The largest free-tailed bat population during winter 2010–2011 was at D'Hanis Bridge with 216,128 bats (± 24,013). We estimated that Old Tunnel State Park had 65,015 (± 1,948) free-tailed bats and Bracken Bat Cave had 15,233 (± 1,223) free-tailed bats during winter 2010–2011. The Chiroptorium contained the smallest population of 635 free-tailed bats (Table 1).

The largest population of free-tailed bats, 254,502 (± 9,255), during winter 2011–2012 was at Old Tunnel State Park. D'Hanis Bridge had the second largest population with an estimated 226,349 (± 25,150) free-tailed bats. We estimated that Bracken Bat Cave contained 88,834 (± 2,232) free-tailed bats. The Chiroptorium again had the smallest estimated population at 885 free-tailed bats. Populations of free-tailed bats at all roosts increased from 2010 to 2011, with Bracken Bat Cave and Old Tunnel State Park roosts showing the largest increases of 480% and 277%, respectively (Table 1).

James River Cave had the lowest mean absolute humidity during both seasons (6.0 g/m^3 in 2010–2011 and 8.0 g/m^3 in 2011–2012). The highest mean absolute humidity was recorded at Davis Blowout Cave for both seasons (9.7 g/m^3 in 2010–2011 and 11.9 g/m^3 in 2011–

TABLE 2—Temperature data (°C) and mean absolute humidity (g/m^3) summaries for sites occupied and unoccupied by *Tadarida brasiliensis* during December 2010–January 2011 and December 2011—January 2012.

	2010–2011					2011–2012				
Site	Mean humidity	Mean temp.	Minimum temp.	Maximum temp.	Temp. range	Mean humidity	Mean temp.	Minimum temp.	Maximum temp.	Temp. range
Davis[a]	9.7	16.6	12.6	20.8	8.3	11.9	17.3	14.5	21.3	6.8
James River[a]	6.0	14.2	9.6	18.5	8.9	8.0	14.9	11.3	19.6	8.4
Chiroptorium	7.3	11.7	3.9	28.3	24.4	9.5	11.7	4.6	24.5	19.9
D'Hanis	7.9	13.0	7.1	19.5	12.4	10.3	13.1	7.5	19.3	11.9
Old Tunnel	7.4	8.6	0.1	16.9	16.9	8.6	9.2	1.9	17.9	16.0

[a] Sites without bats.

2012). The lowest mean temperature was recorded in Old Tunnel State Park for both seasons (8.6°C in 2010–2011 and 9.2°C in 2011–2012). The highest mean temperature was recorded in Davis Blowout Cave for 2010–2011 and 2011–2012 at 16.6°C and 17.3°C, respectively. Temperatures appeared to be more stable at unoccupied roosts. The temperature at Davis Blowout Cave fluctuated by 8.3°C during 2010–2011 and by 6.8°C during 2011–2012. Temperature ranges at James River Bat Cave were similar to Davis Blowout Cave at 8.9°C during 2010–2011 and 8.4°C during 2011–2012 (Table 2). Results of the Pearson's correlation coefficient showed significant correlation between internal and external temperatures at both unoccupied ($r_{33} = 0.51$, $P < 0.001$) and occupied ($r_{52} = 0.85$, $P < 0.005$) roosts.

During our study we also discovered populations overwintering at two bridges in Hays County, Texas. One was located in San Marcos at I-35 and Centerpoint Road (Hays County, 29°49′40″N, 97°59′07″W), and another in Wimberley on Ranch Road 12 at the Cypress Creek crossing (Hays County, 29°59′48″N, 98°05′51″W). These sites were discovered after analyses had begun. Therefore, population sizes and microclimates were not assessed. Another overwintering population, previously documented by Keeley and Keely (2004), at McNeil Bridge on I-35 (Round Rock, Williamson County, 30°30′08″N, 97°40′58″W) sustained high mortality after prolonged freezing temperatures in late January and early February 2011 (Fran Hutchins, Bat Conservation International, pers. comm.).

DISCUSSION—We confirmed the presence of previously unreported overwintering free-tailed bat populations and established baseline estimates at four roosts in central Texas. Recoveries of banded free-tailed bats in central Texas during winter were reported as early as 1952 (Glass, 1982). However, no attempts were made to determine roosting locations. Glass (1982) concluded that free-tailed bats did not occur above the southern edge of the Edward's Plateau region of Texas during winter, and the winter range was between 29°N and 20°N. All occupied winter roosts in our study occur north of 29°N. These results might indicate a northward expansion in Texas of the winter range for the species.

In addition, Eads et al. (1957) reported no overwintering bats at Bracken Bat Cave during three consecutive winters in the 1950s. This also suggests a slight northward expansion of the winter range during the last 50 years. We also documented increases in bat populations at all occupied roosts. Continued monitoring of roosts and populations are needed to document any further northward expansion of the overwintering range as well as to determine whether overwintering populations are actually increasing. It is possible the increase was an isolated incident possibly caused by weather-driven fluctuations, resource availability, or both.

Upon analysis of microclimate data, it appears that free-tailed bats potentially select colder, less stable roosting environments during winter in central Texas. However, because of low sample size we are unable to confirm this statistically. Free-tailed bats in Louisiana have been documented to enter torpor at temperatures as high as 17°C (LaVal, 1973). Although mean temperatures were at or below 17°C at unoccupied sites, they were 4.56°C higher on average and more stable than occupied sites (Table 2). Results also indicated that roost temperature patterns at all sites were significantly correlated with external temperatures. However, Pearson's correlation coefficient signified that a stronger correlation existed at occupied roosts. Figures displaying weekly patterns for each site can be found in Weaver (2012). Research suggests that bats inhabiting winter sites with strongly correlated internal and external roost temperatures can evaluate external conditions without emerging, which is energetically costly (Speakman and Racey, 1991; Hays et al., 1992). In addition, correlation of internal to external roost temperatures has been discovered in hibernacula of several other species of bats (Ransome, 1968; Daan, 1973). It also has been found that bats preferentially emerge during warmer evenings (Ransome, 1968; Avery, 1985; Brack and Twente, 1985) and will not emerge on cold nights when food may be unavailable (Hays et al., 1992). Temperatures that define cold nights can vary on the basis of invertebrate activity (O'Donnell, 2000). Therefore, higher temperatures that are not as closely correlated with external temperatures might explain the absence of bats at James River Bat Cave and Davis Blowout Cave.

The range for mean relative humidity values recorded at all sites was within the accepted range for survival of free-tailed bats (10–100%; Twente, 1956; Herreid, 1963). This, combined with low sample size, makes drawing conclusions on the basis of humidity difficult. It is possible that humidity might be a factor influencing roost site selection at other sites, along with unmeasured variables, such as airflow (Tuttle and Stevenson, 1981).

It is not clear at this time whether free-tailed bats present during winter are summer residents of the respective roost sites, or northern migrants short-stopping on historical migration routes into Mexico (Geluso, 2008). In either case, shifts in the winter range of free-tailed bats could be related to prey species. Primary food sources of free-tailed bats during summer in central Texas are the corn earworm (*Helicoverpa zea*) and fall armyworm (*Spodoptera frugiperda*) moths, species in the order Lepidoptera. Both are facultative migratory insects that are considered major crop pests in Texas (Whitaker et al., 1996; Lee and McCracken, 2002). McCracken et al. (2008) suggested that distribution of free-tailed bats in Texas can be associated with distributions of these migratory moths. It is possible that free-tailed bats are expanding the winter range northward as their prey species enlarges its distribution. If this scenario is correct, it could have profound economic implications for both Texas and Mexico because of impacts on the agricultural industry (Cleveland et al., 2006; Federico et al., 2008). Recent research on the dietary habits of free-tailed bats during winter at Old Tunnel, D'Hanis Bridge, and the Chiroptorium reported Lepidoptera as third most common insect order occurring in fecal samples, establishing that moths are present in diets of free-tailed bats during winter months in Texas (Ramirez, 2014). It has also been suggested that a decrease in migration survival due to factors such as climate change and wind energy development could lead to a decrease in migratory distance of free-tailed bats (Wiederholt et al., 2013) and might also explain the establishment of new overwintering roosts in central Texas.

In relation to estimating population sizes, many challenges arose during the course of our research. The difficulties of enumerating bat colony sizes are well known (Constantine, 1967; Humphrey, 1971; Kunz, 2003; McCracken, 2003; Hristov et al., 2010). Combining digital photographs with a laser caliper greatly increased the accuracy of population estimates (Meretsky et al., 2010). However, analyzing photographs does not account for irregularities in walls and ceilings of roosts. Therefore, our population estimates for Old Tunnel State Park and Bracken Bat Cave are believed to be conservative. Thermal imaging might potentially be a better method in such situations (Betke et al., 2008; Hristov et al., 2010). However, this method requires an emergence from the roosting site, which can be unpredictable during winter (Geluso, 2008).

Winter months are critically sensitive time periods for bats in which disturbance to roosts can be detrimental (Thomas, 1995). Many of the roosts in central Texas have been mined for guano for decades (Betke et al., 2008). Historically, free-tailed bats did not occur in these locations during such activities and therefore disturbance to roosting bats was not a concern. However, our research suggests that free-tailed bats are establishing overwintering colonies in these sites previously unoccupied during winter. During our study, Frio Bat Cave was dropped from our analyses because of guano mining disturbance. There was an established winter colony that existed at the start of guano mining operations in December 2011. During the mining, the colony exited the cave and did not return. The temperatures were below freezing and the exit occurred during daytime hours, suggesting that the bats left as a result of the mining operations. Where newly established overwinter colonies occur, land owners should consider the impacts of guano mining and roost disturbance.

Furthermore, if global climate change is influencing shifts in the overwintering range of free-tailed bats, then continued changes in the winter distribution can be expected (Scheel et al., 1996; Popa-Lisseanu and Voigt, 2009). It is also critically important to continue monitoring bat populations as WNS spreads throughout the United States (Blehert et al., 2009; Cohn, 2012). The effect, if any, of WNS on free-tailed bats is not known, but sympatric species known to roost with free-tails (e.g., big brown bats [*Eptesicus fuscus*]; Wilkins, 1989) are affected (Blehert et al., 2009). Therefore, the potential for free-tailed bats to spread the disease is of great concern.

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