Thermally-assisted monitoring of bat abundance in an exceptional cave in Brazil's Caatinga drylands

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Caves are very important roosts for bats. Neotropical countries, like Brazil, harbor both high bat species richness and abundance of underground cavities. The Caatinga drylands in northeastern Brazil are a good example with potentially 100 bat species and a high number of caves. Among those caves, some harbor exceptionally large bat populations, but, even thus, they still remain poorly known and studied. Here we present a 48-months monitoring based on a non-invasive thermal detection system to estimate the abundance changes of a large colony in a bat cave in the Caatinga drylands of Brazil. That cave harbors ten bat species — two nationally endangered — and 70% of them are main cave users. We found a marked inter-month fluctuation in the total bat abundance, with no consistent pattern. Total bat abundance was neither related to precipitation nor to the reproductive seasonality. During certain moments, the bat population can reach up to 120,000 individuals, making this cave a priority site for bat conservation in Brazil.

Key words: bat abundance, cave-dwelling bats, Caatinga, cave conservation

INTRODUCTION

Bats use a great variety of diurnal roosts such as mines, tunnels, foliage leaves, tree hollows, rock crevices and caves (Kunz, 1982). Caves are one of the most common day roosts and permanent shelters used by bats because they maintain more stable climatic conditions and offer protection against predators during the day (Ávila-Flores and Medellín, 2004; Furey and Racey, 2016). Moreover, caves are roosts used for some vital activities such as reproduction, offspring care and social interactions (Altringham, 2011; Furey and Racey, 2016). Caves exhibit microclimate stability in temperature and humidity across the day and seasons. Stable microclimatic conditions are important factors of roost selection by bats (Rodríguez-Durán and Soto-Centeno, 2003).

Underground roosts can be essential for bat survival at a global level (Mickleburgh *et al*., 2002). In the Tropics, high levels of cave occupancy by bats has been reported (Arita, 1993; Rodríguez-Durán, 2009; Furey *et al*., 2010; Luo *et al*., 2013). This situation prevails in Brazil, which has both high bat species richness (182 species so far — Nogueira *et al*., 2018) and high cave potential (estimated at > 310,000 — Piló and Auler, 2011), stressing the large potential for research on cave-dwelling bats in the country. The distribution of caves is spatially heterogeneous in Brazil (Jansen *et al*., 2012; CECAV, 2018), with some regions having more than others. For instance, at least 72 species of bats use caves in Brazil (Oliveira *et al*., 2018) and cave protection had been identified as a priority for bat conservation in Brazil (Bernard *et al*., 2012).

The Caatinga drylands of northeastern Brazil is largely karst habitat with many caves (Jansen *et al*., 2012; CECAV, 2018). Furthermore, so far, most of the known bat caves in Brazil are located in the Caatinga drylands. Bat caves are roosts harboring exceptional bat populations, frequently surpassing 100,000 individuals (e.g., Ladle *et al*., 2012). Although known and studied in other countries

in Central America, the Caribbean and North America (e.g., Corso *et al.*, 2012; Ladle *et al.*, 2012; Medellín *et al.*, 2017), Brazilian bat caves are poorly known and just recently have received more attention. But, even thus, there are few studies focused on those exceptional roosts and on the biology of the cave-dwelling bats there. Recent studies revealed Caatinga's high bat species richness (at least 96 species, including two endemics), but there is a huge need to fill basic gaps on the biology and ecology of the species present there (Silva *et al.*, 2018). Moreover, since 2009, changes in the Brazilian cave protection policies state that a cave will be considered under protection only after an evaluation of its relevance at both local and regional level (MMA, 2009). In practice, that modification reduced cave protection in Brazil opening space for negative impacts from mining or other extractive activities (Bernard *et al.*, 2012).

The Caatinga dry lands are dominated by seasonally dry tropical forest (SDTF), and similarly to other semiarid regions, annual rainfall varies widely. There are seasonal restrictions in the availability of water and food resources. Bats occurring there have a variety of behavioral adaptations such as dietary flexibility, long and short migrations, adjustments in activity patterns and synchronizing reproduction with periods of food abundance (Stoner and Timm, 2011). In SDTF, bat species tend to reproduce seasonally and in several localities birth and lactation usually occurs at the beginning and middle of the rainy season (Stoner and Timm, 2011). In SDTF, bat species tend to show seasonal repro-duction and in several localities births and lactation usually occurs at the beginning and middle of the rainy season (Stoner *et al.*, 2003; Bumrungsri *et al.*, 2007; Stoner and Timm, 2011). Overall we lack detailed information about reproductive behavior of cave-dweller bats in Brazil's Caatinga.

Our goal is to describe and estimate the abundance changes of a large colony in a bat cave in the Caatinga drylands of Brazil. We tested possible associations with rain patterns, and expected that bat abundance would be positively associated with rainfall. Additionally, we provide information about the reproductive cycle of the bat species found in that cave, predicting that bat reproduction would occur during the rainy season. To achieve these goals, we analyzed data from a 48-months monitoring based on a non-invasive thermal detection system.

MATERIALS AND METHODS

Study Area

Field work was carried out in the cave Meu Rei (08°29'14.1"S, 37°16'48.8"W) located in Catimbau National Park, Pernambuco state, northeastern Brazil, a semiarid region dominated by seasonally dry tropical forest (Silva *et al.*, 2017). Environmental average temperature is almost constant over the year, ranging from 25°C to 30°C, while average annual rainfall shows a high variation in time and space, where 75% of the region receives annual precipitation between 600 and 1,200 mm (Andrade *et al.*, 2017). Meu Rei cave is 162.5 m long, has one entrance and four chambers, is formed by arenitic rock (CECAV, 2014) and can be considered a bat cave due to the large colony using it as a roost.

Bat Captures and Collection of Biological Data

Bat species identification and presence in the cave were confirmed through direct observation and captures with a hand net and a harp trap. Information on individual body mass, sex, reproductive condition and age were taken from captured bats. Based on cave usage, species were classified following Arita (1993) and Guimarães and Ferreira (2014), considering three categories: 1) main cave users — for those species whose caves are their principal roost; 2) regular cave users — for species which use caves regularly but have some alternative roosts; and 3) not known cave users — for bat species that were not reported in caves. Additionally, we determined the species' feeding guild following Kalko *et al.* (1996). Species' conservation status was determined at national level, following Brazil's National Red List (MMA, 2014), and at the global level, using the IUCN categorization (IUCN, 2018). Capture and handling methods followed the guidelines of the American Society of Mammalogists (Sikes *et al.*, 2011). Bat captures were authorized by licenses from MMA/ICMBio/SISBIO (#62738-1, #43816-1, #43816-2, #44032-2, #23576-1) and the Ethics Committee on Animal Care–UFPE (#23076.027916/ 2015-13).

Bat Abundance Estimation

Estimations of animal abundance and fluctuations over time are critical elements for understanding the relationship between organisms and their environment (Brown *et al.*, 1995). However, in the case of bats, achieving reliable estimates of large aggregations — such as those observed in caves — is a scientific challenge (Kunz, 2003; Kunz *et al.*, 2009). Common methods used for estimating bat abundance in caves frequently involve visual counting (Arita, 1996), photographic estimation (Corso *et al.*, 2012; Deleva and Chaverri, 2018), mark-recapture (Torres-Flores *et al.*, 2012), acoustic recordings (Kloepper *et al.*, 2016) and thermal imaging recording (Betke *et al.*, 2008; Hristov *et al.*, 2010). All those methods have pros and cons, and both visual counting and photographic estimations are the most common methods used to determine bat abundance in tropical caves. Even though these two methodologies are easy to use in the field and are low-priced, both can lead to biased estimates especially for highly gregarious species (Kunz *et al.*, 2009).

Here we used a non-invasive thermal detection system to count bats in Meu Rei cave and estimate abundance changes. Meu Rei was sampled along two consecutive days every month

from October 2014 to April 2018 and in only one night from June 2018 to October 2018. Bat abundance was estimated based on video recordings of bat emergence using a thermal infrared camera (FLIR, Series E60) installed at the cave entrance. Recordings were made from the beginning of bat activity until no emergence was detected, usually during one hour (from 17:30 to 18:30, approximately). We considered the maximum counting obtained each month, except for January and February of 2016 when climatic conditions only allowed to record one night and, for April 2017, when one of the videos failed. No data is available for May 2017, January and May of 2018. We compared the number of bats counted in the first night against the second night using a Mann-Whitney test. The infrared camera produced an image with 320×256 pixels, captured at 30 Hz. The number of bats was automatically estimated using an algorithm specially designed for tracking and counting bats (Rodrigues *et al.*, 2016). Lab validations of the algorithm indicated error margins < 6%, with an average error of ca. 3%. In addition to the assessment of the total number of bats in the cave we visually estimated colony sizes for each species before cave emergence.

Data on monthly precipitation from October 2014 until October 2018 were based on information from the nearest weather station, ca. 25 km from the cave (INPE/SUDENE/CPTEC, 2018). We analyzed the variation of bat abundance between sampling years using a generalized linear model (GLM) with sampling year as factor and precipitation as a covariate, using a quasi-Poisson error structure. The relationship between bat abundance and precipitation was examined by cross-correlation analysis using the package astsa (Stoffer, 2019). All analyses were conducted in the program R v.3.4.4 (R Core Team, 2018). Values are expressed as mean ± SD and results were considered significant at $P \leq 0.05$.

Results

Species Richness, Feeding Guilds and Species' Conservation Status

We recorded ten species of bats roosting in the cave Meu Rei during the whole sampled period: seven Phyllostomidae, two Mormoopidae (*Pteronotus gymnonotus* and *Pteronotus personatus*) and one Natalidae (*Natalus macrourus* — Table 1). *Pteronotus gymnonotus*, *N. macrourus*, *Carollia perspicillata* and *Diphylla ecaudata* were the most frequently captured species, observed almost during the entire sampled period. *Desmodus rotundus* was not recorded in 2014/2015 but recorded regularly during 2016 and sporadically in 2017 and 2018. *Anoura geoffroyi* was frequently observed between December to April of the years 2015 and 2016, but since 2017 was rarely observed. Species such as *Glossophaga soricina* and *Lonchorhina aurita* were captured or observed sporadically during the sampling period. *Pteronotus personatus* was only recorded in April and July 2017 and captured sporadically in three months of 2018. *Tonatia bidens* was just captured in March 2015 and observed in April 2018 (Fig. 1). The cave-dwelling species we recorded in Meu Rei showed high roost fidelity. Species such as *C. perspicillata*, *G. soricina*, *D. ecaudata*, *A. geoffroyi* and *D. rotundus* were always observed in the same location inside of the cave along all the months sampled. Species such as *N. macrourus*, *L. aurita* and *T. bidens*, which were difficult to observe because are very sensitive to cave disturbing, were registered most of the time in the same places. In fact, between July 2017 and October 2018 we directly sighted only one individual of *T. bidens*, but we found fresh guano every month under the same place used by this species. Species such as *P. gymnonotus* and *P. personatus* were generally restricted to the inner camera of the cave.

Species such as *P. gymnonotus*, *P. personatus*, *N. macrourus*, *D. rotundus*, *D. ecaudata*, *A. geoffroyi* and *L. aurita* were the main cave users, while *C. perspicillata*, *G. soricina* and *T. bidens* used caves as regular shelters. Foraging mode diversity was high: three aerial insectivores, one gleaning insectivore, two gleaning nectarivores, two gleaning

TABLE 1. Cave use, conservation status and feeding guild of bat species registered in Meu Rei cave, NE Brazil from October 2014 to April 2018

Species	Cave use	Status IUCN	Status Brazil	Feeding guild
Pteronotus gymnonotus	Main	LC		Aerial insectivore
Pteronotus personatus	Main	LC		Aerial insectivore
Natalus macrourus	Main	NT	VU	Aerial insectivore
Carollia perspicillata	Regular	LC		Gleaning frugivore
Desmodus rotundus	Main	LC		Gleaning sanguivore
Diphylla ecaudata	Main	LC		Gleaning sanguivore
Anoura geoffroyi	Main	LC		Gleaning nectarivore
Glossophaga soricina	Regular	LC		Gleaning nectarivore
Lonchorhina aurita	Main	LC	VU	Gleaning insectivore
Tonatia bidens	Regular	DD		Gleaning animalivore*

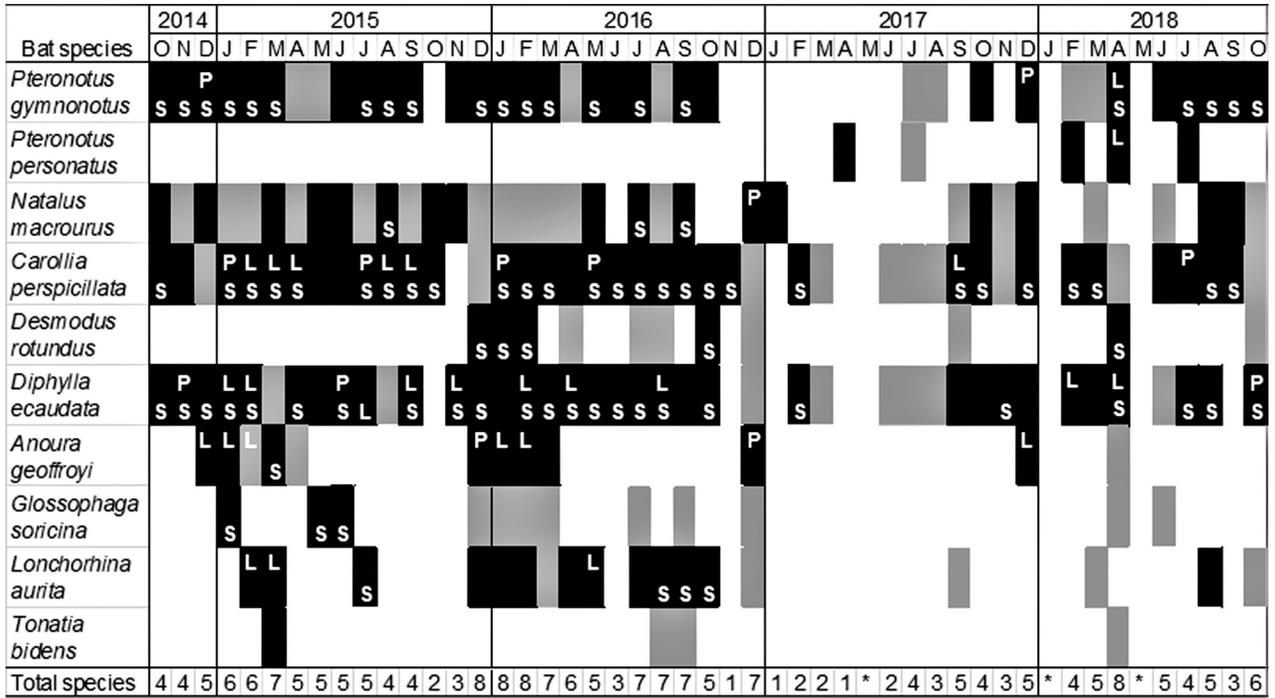* — Considered as animalivorous because we observed insects and bird remains in the guano

Bat species	2014 O N D	2015 J F M A M J J A S O N D	2016 J F M A M J J A S O N D	2017 J F M A M J J A S O N D	2018 J F M A M J J A S O
Pteronotus gymnonotus	P S S S	S S S S S	S S S S S S S	P	L S L S S S S
Pteronotus personatus					L
Natalus macrourus		S	S S	P	P
Carollia perspicillata	S	P L L L S S S S P L L S S S S	P S S S P S S S S S S S	S L S S S	S S P S S
Desmodus rotundus			S S S S		S
Diphylla ecaudata	P L L S S S S S	P L S S L L S S S S	L L L L L S S S S S S S S	S	L L S S S S P S S
Anoura geoffroyi	L L L S		P L L	P	L
Glossophaga soricina		S S S			
Lonchorhina aurita		L L S	L S S S		
Tonatia bidens					
Total species	4 4 5	6 6 7 5 5 5 5 4 4 2 3	8 8 7 6 5 3 7 7 7 5 1 7	1 2 2 1 * 2 4 3 5 4 3 5	* 4 5 8 * 5 4 5 3 6

FIG. 1. Bat species captured (black) and observed (gray) from October 2014 to October 2018 in Meu Rei, a bat cave in NE Brazil. P — pregnant, L — lactating, S — scrotal. Absence of letters indicates that individuals were non-reproductive. * — No data

sanguivores, one gleaning frugivore and one gleaning animalivore (Table 1). At national level, *N. macrourus* and *L. aurita* are included in the Brazilian Red List, both categorized as Vulnerable (http://www.icmbio.gov.br/portal/faunabrasileira/lista-de-especies). At global level, *N. macrourus* was categorized as Near Threatened, eight other species as Least Concern, and *T. bidens* as Data Deficient (www.redlist.org).

Reproductive Behavior

Pteronotus gymnonotus, N. macrourus, L. aurita and A. geoffroyi showed one reproductive season per year (Fig. 1). Three pregnant females of *P. gymnonotus* and one of *N. macrourus* were captured only in December. Scrotal males of *P. gymnonotus* were commonly found along the sampling, while only three scrotal male of *N. macrourus* were captured once in 2015 (August) and twice in 2016 (July and September — Fig. 1). We captured lactating females of *L. aurita* in the first trimester of 2015 (*n* = 5) and in May, July and September 2016 (*n* = 4), while scrotal males were registered in 2015 (July, *n* = 2) and 2016 (August–October, *n* = 6 — Fig. 1). Pregnant and females with nursing bats of *A. geoffroyi* were registered only at the ending of the year (December to February, *n* = 19), while only two males were captured in the first

trimester of 2015 (scrotal) and 2016 (non-scrotal) (Fig. 1).

Only *D. ecaudata* (seven pregnant and ten lactating females) and *C. perspicillata* (four pregnant and 19 lactating) displayed two reproductive seasons per year, with both species captured at the beginning and middle of the year. Scrotal males of *D. ecaudata* (*n* = 36) and *C. perspicillata* (*n* = 66) were observed during almost all sampled months (Fig. 1). We only captured two non-reproductive females and three scrotal males of *G. soricina* in 2015 (January, May and June). For *D. rotundus*, we gathered information for scrotal males for only six bats captured in 2015, 2016 and 2018 (Fig. 1). We only captured one lactating female of *P. personatus* in April 2018 and only one non-reproductive female of *T. bidens* in 2015 (Fig. 1). The low number of captures of *G. soricina*, *D. rotundus*, *P. personatus* and *T. bidens* did not allow us to give an accurate description of the reproductive patterns for these species.

Bat Abundance in Meu Rei Cave

Total bat abundance fluctuated by month, from 118,946 individuals in August 2015, to 95 bats in November 2016, with no consistent abundance pattern (Fig. 2). Abrupt variations in bat abundance occurred between samplings, with the number of individuals increasing up to 158 times (e.g., 147 bats

in March 2017, and 23,298 bats in April 2017). There was no pattern in the number and temporality of the abundance peaks during each sampling year. For example, there was only one evident peak in the first (October 2014–September 2015) and second (October 2015–September 2016) years of sampling, and it happened in different months (August 2015 and May 2016, respectively). In contrast, during the third year of sampling (October 2016–September 2017) we observed two marked abundance peaks, and three during the fourth year (October 2017–September 2018), but none as high as in the previous years. We observed a slight variation in the estimate of the number of bats between the two nights of recordings, in the first (October 2014–September 2015) and second (October 2015–September 2016) years of sampling. Nevertheless, the difference between nights was not statistically significant ($W = 869$, $P = 0.38$).

Colonies sizes in Meu Rei varied by species during the sampled period. While *G. soricina*, *D. rotundus*, *A. geoffroyi* and *N. macrourus* formed small groups with less than 25 bats, *T. bidens* had a single individual recorded, and species such as *C. perspicillata*, *D. ecaudata* and *L. aurita* aggregated in colonies of intermediate size (25–100 bats). The large variation in bat counts was caused mainly by fluctuations in numbers of *P. gymnonotus*, which formed large colonies, from hundreds to more than one hundred thousand bats. Individuals of *P. personatus* were observed mixed with individuals of *P. gymnonotus*, making it difficult to establish an estimation of colony size for the first. So, in fact, higher and lower peaks of total abundance in the cave were basically determined by fluctuations of *P. gymnonotus*.

Bat abundance in the cave was not significantly different between the sampled years (Deviance = 845,222, *d.f.* = 44, $P = 0.29$) and was not significantly affected by precipitation ($P = 0.75$). Although the number of individuals was not significantly different between years, we observed a higher abundance in the first year of sampling ($14,552 \pm 3,312$ bats) than during the second, third and fourth year of sampling ($5,859 \pm 9,365$, $6601 \pm 11,730$ and $6,084 \pm 8,038$ bats, respectively). Monthly precipitation was not significantly different among the sampled years (Deviance = 1,839.8, *d.f.* = 44, $P = 0.98$). Highest annual average precipitation was observed between October 2016 to September 2017 (55.72 ± 58.46 mm).
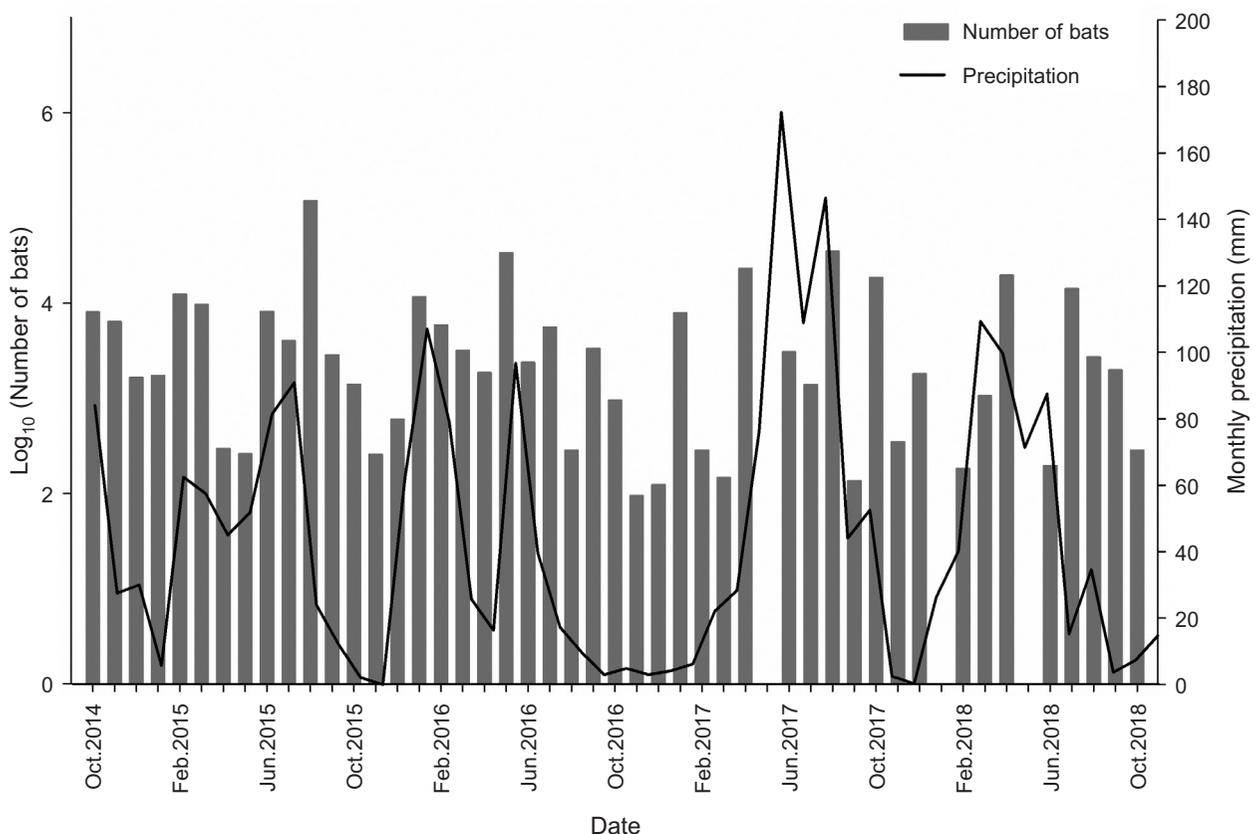

Fig. 2. Bat abundance and monthly precipitation from October 2014 to October 2018 in Meu Rei, a bat cave in NE Brazil

TABLE 2. Number of bats counted during each sampling month and each night, based on video recordings in Meu Rei cave, NE Brazil

Month	Number of individuals		
	Night 1	Night 2	Maximum
October 2014	5,613	8,069	8,069
November	6,385	6,037	6,385
December	438	1,658	1,658
January 2015	1,742	1,667	1,742
February	12,486	11,570	12,486
March	9,684	5,138	9,684
April	297	208	297
May	135	262	262
June	5,920	8,199	8,199
July	4,045	3,956	4,045
August	96,672	118,946	118,946
September	2,196	2,850	2,850
October	1,406	486	1,406
November	258	235	258
December	437	602	602
January 2016	11,655	ND	11,655
February	5,932	ND	5,932
March	3,182	1,767	3,182
April	1,873	773	1,873
May	30,897	33,785	33,785
June	2,391	273	2,391
July	2,229	5,575	5,575
August	200	284	284
September	3,365	2,306	3,365
October	949	401	949
November	76	95	95
December	124	120	124
January 2017	7,934	7,077	7,934
February	223	286	286
March	146	147	147
April	23,298	ND	23,298
May	ND	ND	ND
June	3,083	1,102	3,083
July	1,391	965	1391
August	35,171	29,836	35,171
September	136	136	136
October	18,587	9,757	18,587
November	163	350	350
December	1,550	1,820	1,820
January 2018	ND	ND	ND
February	162	183	183
March	1,066	170	1,066
April	258	19,694	19,694
May	ND	ND	ND
June	197	*	197
July	14,219	*	14,219
August	2,733	*	2,733
September	1,989	*	1,989
October	286	*	286

* — Only one night of video recordings; ND — no data

From July 2016 until March 2017 we observed the longest dry season, with less than 30 mm of rain (Fig. 2). According to the cross-correlation analysis, the number of bats was not significantly related to the precipitation pattern (Fig. 3).

DISCUSSION

The 48-months monitoring of Meu Rei cave in the Caatinga drylands of northeastern Brazil indicated a highly variable monthly and annual abundance. Precipitation did not explain such variation since there was no correlation between the monthly amount of rain and the number of bats using the cave. Based on our best knowledge, this is the first monitoring carried out in a Neotropical cave which shows bat abundance variation based on a standardized, observer-independent quantitative estimate. Moreover, this is the first bat cave in Brazil — subject to long-term standardized censuses, making our monitoring the first to deliver reliable data on bat abundance and species presence in any given cave in the country.

Bat Species Richness

Most of the species recorded in Meu Rei are considered as cave specialists and its richness is high when compared with caves in other tropical localities in Mexico (Arita, 1993; Ayala Téllez *et al.*, 2018), Colombia (Muñoz-Saba *et al.*, 2007; Pérez-Torres *et al.*, 2015), China (Luo *et al.*, 2013), Costa Rica (Deleva and Chaverri, 2018) and Brazil (Silva *et al.*, 2009; Guimarães and Ferreira 2014; Felix *et al.*, 2016; Oliveira *et al.*, 2018; Vargas-Mena *et al.*, 2018). Richness ranged from three to six species in most of those caves, and only 10–13% of them had more than six bat species. Meu Rei cave has also one of the highest bat species richness when compared with other caves in the Caatinga region (Gregorin *et al.*, 2008; Sbragia and Cardoso, 2008). Only Furna Feia cave, in the nearby Rio Grande do Norte state, had also ten bat species recorded (Vargas-Mena *et al.*, 2018).

Bat Abundance and Precipitation

Bat abundance in Meu Rei cave showed a notable fluctuation during all months sampled and its variation was related with the periods of absence and presence of the large aggregations of *P. gymnonotus* and *P. personatus* — specially the first. In line with our results, studies carried out in other tropical and temperate caves with large bat populations have shown that bat abundance may vary along the time (Hristov *et al.*, 2010; Torres-Flores *et al.*, 2012; Rocha and Bichuette, 2016), and such fluctuations have been interpreted as a response to both the seasonality of food resources and climatic variables, such as
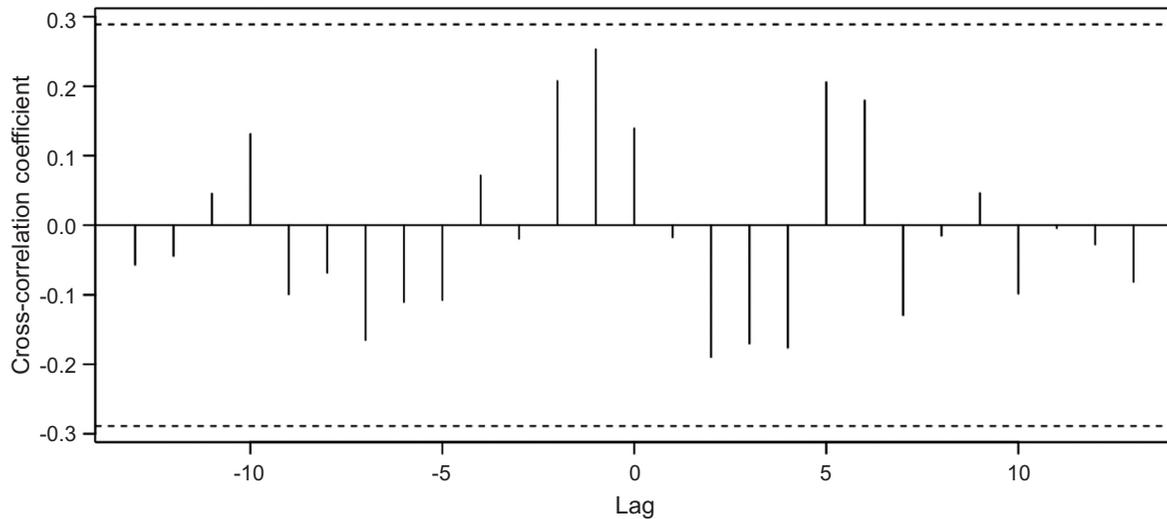
FIG. 3. Cross-correlation of number of bats with precipitation in Meu Rei cave in NE Brazil. The cross-correlation coefficient is a measure of similarity of two series as a function of the displacement (also known as lag) of one relative to the other. The lag is expressed in days and higher peaks around lag 0 would indicate an autocorrelation between bat abundance and precipitation. However, peaks at other lag values indicated that the number of bats detected was not significantly related to the precipitation pattern. Dashed lines indicate limits for statistical significance of 95%

precipitation. For example, in a cave located in a dry forest in Mexico, aerial insectivorous species of the genera *Pteronotus* and *Natalus* were more abundant from the ending of the dry season until the beginning of the rainy season, when the highest abundance of insects was observed (Torres-Flores *et al*., 2012). Although our data showed that bat abundance was not significantly related with precipitation, we observed that higher abundances of *P. gymnonotus* and *P. personatus* mostly occurred at the end of the rainy season (Fig. 2). Similarly, the highest abundance of other aerial insectivores, like *Tadarida brasiliensis* in the Carlsbad Cavern in New Mexico, was observed during the rainy season, when the availability of insects increased (Hristov *et al*., 2010).

The Caatinga ecosystem shows a highly variable precipitation regime, and wide annual variations and periodic droughts are frequent (Silva *et al*., 2017). For example, an extremely long period of drought occurred between July 2016 and March 2017, coincidentally when we observed the lowest bat abundances in the cave, with sporadic observations of *P. gymnonotus*. The reasons behind the absence of those bats during that period remains unknown, but it could be possibly related to the species' reproductive patterns or due to regional food availability fluctuations. Meu Rei does not present the unique hot chambers used by pregnant *Pteronotus* females to give birth and feed their newborns (Rodríguez-Durán, 1998, 2009; Rodríguez-Durán and Soto-

Centeno, 2003), and is very likely that the extreme fluctuations observed are more related with copulatory behavior — i.e., bats may be using that cave for copula, but not as a maternity roost (see the next topics in the Discussion). Moreover, although we did not collect insects as part of our study, the incidence of the rainy pattern on the insect population dynamics has been documented for several localities in the Caatinga, where several orders of insects such as Coleoptera, Hymenoptera, diurnal and nocturnal Lepidoptera were more abundant during the rainy season (Gusmão and Creão-Duarte, 2004; Vasconcellos *et al*., 2010; Nobre *et al*., 2012). The long-term monitoring of Meu Rei cave continues, and clear seasonal patterns may arise in the future.

Bat Abundance and Reproductive Seasonality

Reproductive pattern observed for *P. gymnonotus*, *N. macrourus*, *L. aurita* and *A. geoffroyi* at Meu Rei cave was similar to seasonal dry forests in the Neotropics, where these species also showed a seasonal monoestrous pattern (Willig, 1985*a*; Stoner *et al*., 2003; Nogueira *et al*., 2007; Sperr *et al*., 2011; Torres-Flores *et al*., 2012; Vásquez-Parra *et al*., 2015). At the Caatinga we captured pregnant females for *P. gymnonotus* and *N. macrourus* at the end of the dry season, a similar pattern for females of *Pteronotus* and *Natalus* in dry forests of Mexico and Venezuela (Torres-Flores *et al*., 2012; Vásquez-Parra *et al*., 2015). The fact that we captured few pregnant females of *P. gymnonotus* and *N. macrourus*

and no nurseries were observed in the cave, may suggest that females of these species leave this roost once pregnant. Our findings about reproductive behavior of *A. geoffroyi* were similar to previous data described for dry forests in Brazil's Cerrado and Caatinga, where pregnancy occurred at the end of the dry season, and lactation at the beginning of the rainy season (Willig, 1985*a*; Zortéa, 2003). Data about the reproductive behavior of *L. aurita* in tropical dry forests are scarce. Although we only captured a few lactating females during the wet season, this reproductive pattern was similar to that described in several localities of tropical rain forests (Fleming *et al*., 1972; Wilson, 1979; Lassieur and Wilson, 1989).

Seasonal bimodal polyoestry observed for *D. ecaudata* and *C. perspicillata* at the Meu Rei cave was similar to reports in other tropical forests (Willig, 1985*b*; Fleming, 1988; Bredt *et al*., 1999; Durant *et al*., 2013). As reported by Willig (1985*b*) in the Caatinga and Cerrado biomes, we observed two reproductive peaks for *C. perspicillata*, with pregnant females at the transition between dry and rainny seasons, and lactating females along the wet season. However, the pattern observed in the Caatinga contrast with the findings of Stoner (2001) in a dry forest of Costa Rica, where she only found a reproductive peak for *C. perspicillata*. Previous research suggested that *D. ecaudata* has a multimodal polyoestry similar to *D. rotundus* (Racey and Entwistle, 2000). However, in the Caatinga, *D. ecaudata* showed a seasonal bimodal polyoestry, with pregnant females during the transition between rainny and dry seasons and lactating females along the wet season. Similarly, two reproductive peaks for this species were also observed in the Cerrado biome (Bredt *et al*., 1999), and Wilson (1979) suggested that these bats have two birth periods per year. Due to reduced captures, patterns for *G. soricina*, *D. rotundus*, *P. personatus* and *T. bidens* are not discussed.

For most Neotropical bat species it has been suggested that reproduction is synchronized with the availability of food resources (Racey and Entwistle, 2000). For frugivores, a correspondence between lactation and fruiting peaks during the rainy season was already detected (Fleming *et al*., 1972). This could be the case for *C. perspicillata*, since most animal-dispersed plants in the Caatinga have fruits during the rainy season (Griz and Machado, 2001). Similarly, previous research on bat-pollinated plants in the Caatinga have shown peaks of floral production along the dry season and at the beginning of the rainy season. Similarly, previous research on bat-pollinated plants in the Caatinga have shown peaks of floral production along the dry season and at the beginning of the rainy season (Vogel *et al*., 2005; Rocha *et al*., 2007), therefore, the reproductive pattern of *A. geoffroyi* could be related with the local availability of floral resources. Similarly births and lactation period of insectivorous bats usually match with higher insect availability in the rainy season (Racey and Entwistle, 2000). In spite of large data gaps, some insect orders tend to be more abundant during the rainy season in the Caatinga (Gusmão and Creão-Duarte, 2004; Vasconcellos *et al*., 2010; Nobre *et al*., 2012), and such higher insect availability could be related with the lactation period observed for *L. aurita*. Although we only captured pregnant females of *P. gymnonotus* in the dry season, we assume that lactation for this species will take place during the wet season, when insects are more abundant.

An Emphasis on Pteronotus

Considering our censuses were strongly influenced by *P. gymnonotus*, this species deserves special attention. In a cave in Mexico, Torres-Flores *et al*. (2012) have found that abundance fluctuations of several species of *Pteronotus* and *Mormoops* were explained by their reproductive behavior: remarkable increases in the number of bats occurred during the period of copula and establishment of numerous bat nurseries. Reproductive cycles of *P. gymnonotus* in Meu Rei cave were not clear, and no interannual pattern was detected so far. Although this was the most abundant species, we only captured three pregnant females in December, and we did not observe neither bat nurseries nor copulas there. Additionally, during the months we found subadults of *P. gymnonotus* we did not observe a significant increase in the bat abundance in the cave.

Species of *Pteronotus* are mainly cave-dwellers (Rezsutek and Cameron, 1993; Patton and Gardner, 2007; de la Torre and Medellín, 2010), and although data about the roosting behavior of these species is still scarce, several studies suggested that they use the caves for different purposes. For example, in the Caribbean and in some localities in South America, some caves are constantly used along the year by thousands of individuals of *Pteronotus* and those caves exhibit constantly higher temperatures (28–40°C) caused by the heat generated by high densities of bats. Those roosts are known as hot caves (Vizotto *et al*., 1980; Rodríguez-Durán, 2009;

Ladle *et al*., 2012). In contrast, other studies indicated that *Pteronotus* had higher abundances during certain moments of the year, followed by drastic decreases in their populations (Bonaccorso *et al*., 1992; Torres-Flores *et al*., 2012). Our data agree with this roosting behavior, suggesting that Meu Rei cave is a temporal satellite shelter, with bats using other nearby roosts for reproduction and for the establishment of bat nurseries. Preliminary field expeditions in the area support this hypothesis: another cave harboring constant colonies of *P. gymnonotus* and *P. personatus* was found 15 km away, with bats using it as a reproduction roost, with high abundance of pregnant females.

In general, cave-dwelling bats have a higher ectoparasite load due to the favorable environmental conditions in these shelters (Patterson *et al*., 2007; Fagundes *et al*., 2017). However, high ectoparasite loads cannot be ruled out as a potential factor influencing *P. gymnonotus* fluctuations. For example, preliminary studies in Meu Rei cave have shown that 88% of *P. gymnonotus* are parasitized by ectoparasitic flies (with an average of seven flies per bat). Interestingly, 97% of individuals of *D. ecaudata* were parasitized showing an average of 26 flies per bat (E. Barbier, unpublished data), but the size of their colony remained stable throughout the study period and was even smaller than the colony observed of *P. gymnonotus*.

New Approaches to Census Bats

Bat abundance observed in Meu Rei cave was remarkable high in comparison with previous information about bat abundance in other tropical caves (Trajano, 1984; Churchill, 1991; Rodríguez-Durán, 1998; Esbérard *et al*., 2005; Silva *et al*., 2009; Pérez-Torres *et al*., 2015; Ayala Téllez *et al*., 2018; Deleva and Chaverri, 2018; Oliveira *et al*., 2018; Vargas-Mena *et al*., 2018). Most of the studies carried out in tropical caves estimate the bat abundance through counting of individuals registered on photos or based in visual estimates. Our study was the first in the Neotropics to use thermal infrared camera to provide an effective methodology to estimate the number of bats in a cave and its emergence pattern. Although this technique does not allow individuals to be identified as to sex or species, the scores produced are much more accurate than those produced by traditional means. In fact, we observed subtle variations between counts in the first and second nights, which would be almost impossible to detect based on traditional techniques. Some of those

variations may indicate that our activity in the cave — even if minimum and as less impacting as possible — might have influenced the bats, with some of them temporarily leaving the cave. But we have also detected the right moment of the *Pteronotus*' arrival, like in April 2018, when the cave was almost empty in the first night (258 bats) and with 19,694 bats in the second night. Nevertheless, colony estimations here presented have higher accuracy due to the automatized process of counting individuals, and lower impact since we did not enter the cave for counting and we did not stay inside of the cave for more than one hour to capture bats. Additionally, although we were not able to identify the bats counted in a species-specific way, the recording and counting methods used here allowed us to detect and count bats independent of their size, speed, behavior or time of departure from the cave. Our approach used moving pixels or 'blobs' (i.e., a group of pixels) and differences in the temperature between moving parts and the background to detect and count bats (Rodrigues *et al*., 2016). Due to technical details, such as proximity or distance of camera and the animal's changing format with open or closed wings, species-specific identification proved to be not possible. Such task was performed during in situ checking inside the cave or by recording and analyzing their echolocation calls when leaving the roost.

Conservation Implications of Meu Rei Cave

Caves are not only biodiversity hot spots in the landscape (Phelps *et al*., 2016), but they also are key elements in the ecosystems. For example, caves supporting high populations of bats exert an impact in the surrounding landscape (Des Marais *et al*., 1980; Kunz *et al*., 2011; Medellín *et al*., 2017). Our data suggest that Meu Rei cave is an important roost in the Caatinga environment. Nearly 70% of the bat species found there are considered as cave specialist and two species (*N. macrourus* and *L. aurita*) are categorized as vulnerable in the Brazilian Red List. *N. macrourus* and *L. aurita* are considered vulnerable in Brazil because they are rare and are strongly associated to caves, their main roosts. Due to cave transformation by anthropic activities, their populations are expected to decline in the next ten years (Bredt *et al*., 2018; Medeiros *et al*., 2018). In such a scenario, Meu Rei cave is a relevant regional roost for the survival of these bat species. In addition to the high species richness of Meu Rei compared to other caves in the Caatinga, there were a significant

variety of feeding guilds, which could be reflected in a varied energy input to the cave in the form of guano, maintaining diverse communities of cave arthropods (Gnaspini-Netto, 1992). Although it has been suggested that bat guano is not the only food source for cave arthropods, higher diversities of guano invertebrates seem to be related with a more diversified number of feeding habits by the bats roosting in a given cave (Salgado *et al.*, 2014). Furthermore, a high number of insectivorous bats roosting in a cave could be beneficial for local agricultural producers: when foraging, several bat species removes important insect quantities every night, including crop plagues (McCracken *et al.*, 2012; Medellín *et al.*, 2017).

Meu Rei cave is inside of a National Park and categorized as having high relevance following the Brazilian environmental policies (MMA, 2009; Azevedo and Bernard, 2015), therefore, it cannot be used or suffers impacts and its main purpose should be a conservation site. Nevertheless, we have shown that Meu Rei is an important temporary shelter for *P. gymnonotus* and *P. personatus* and they still requires other caves for reproduction in the area. Therefore, in order to guarantee the survival and continuity of these species in the area, those other roosts have to be identified and protected, even if located outside Catimbau National Park. Finding such other roosts is, therefore, essential for effective bat conservation, and the area around any bat cave should be a priority for roost inventories. In fact, studies in Mexico and the USA have shown that bat caves are providers of ecosystem services to vast areas surrounding them, in the order of hundreds of thousands of square kilometers (Medellín *et al.*, 2017).

Meu Rei is one of the bat species-richest caves in Brazil's Caatinga, with ten species. A large colony of *P. gymnonotus* and *P. personatus* used that cave as a temporal refuge, without a clear pattern in the monthly abundance fluctuation. Although we did not find any correlation between bat abundance and the rainy regime in the area, it is likely that this variation reflects other ecological dynamics of these bat species such as male migratory behavior or dynamical movements between different roosts in the area. Future work focused on studying the movements of these two bat species between several caves in the area could bring more information to elucidate the migration pattern at a landscape-level and would provide further data to understand the roost selection and ecology of these mormoopid species.

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