New records, potential distribution, and conservation of the Near Threatened cave bat *Natalus macrourus* in Brazil

Mariana Delgado-Jaramillo, Eder Barbier and Enrico Bernard

Abstract Species with specific roosting, foraging or breeding requirements are particularly vulnerable to habitat loss and degradation. For bats, the availability and environmental condition of caves can be a limiting factor. The cave specialist *Natalus macrourus* (formerly *Natalus espiritosantensis*) is categorized as Near Threatened on the IUCN Red List but as Vulnerable in Brazil, based on a projected population reduction and a decline in its area of occupancy, extent of occurrence and/or quality of habitat. There is a lack of knowledge about the species' distribution, natural history and ecology, information that is required for conservation. Using new occurrence data and potential distribution modelling we evaluated the distribution of *N. macrourus* in Brazil, analysed pressures on and threats to the species, and assessed the species' conservation needs. *Natalus macrourus* is positively associated with areas with higher probability of cave occurrence and negatively associated with areas of high variation in mean daily temperature and mean annual rainfall. Areas with high environmental suitability for *N. macrourus* correspond to only 3% of the potential distribution modelled. We estimate that the species has already lost 54% of its natural habitat and that there is < 35% of habitat remaining in areas with high environmental suitability. We calculated that approximately half of the caves in areas with high environmental suitability are < 5 km from mining operations and only 4% of the species' potential distribution lies within protected areas. Given the strong association of *N. macrourus* with caves, it is important to protect these habitats, and we recommend that caves where the species is present should receive immediate protection.

Keywords Caatinga, caves, Chiroptera, MaxEnt, Natalidae, *Natalus macrourus*, species distribution modelling, threatened species

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Introduction

Species with specific roosting, foraging and/or breeding requirements tend to be particularly vulnerable to habitat loss and degradation (e.g. Jones et al., 2003; Cardillo et al., 2005; Davidson et al., 2009). In the case of bats, the availability and environmental condition of caves can be a limiting factor for several species (Glover & Altringham, 2008), and the conservation of caves is frequently highlighted as being a priority for bats (Arita, 1996; Goodman et al., 2005; Kingston, 2010; Bernard et al., 2012).

Endemic to the Neotropics, species of the family Natalidae are considered to be cave specialists (Tejedor, 2011). These insectivorous bats have funnel-shaped ears, and their tails are usually longer than their total body length (Gardner, 2008; Tejedor, 2011). All males have a natalid organ, located on the dorsal surface of the muzzle, which secretes a substance that can facilitate intraspecific communication (Tejedor, 2011). Bats of this family are light (2–12 g) and small (forearm length 26–51 mm; Tejedor, 2011). Currently, there are three extant recognized genera in the family: *Chilonatalus, Natalus* and *Nyctiellus* (Morgan & Czaplewski, 2003; Tejedor, 2011; Nogueira et al., 2014).

Eight species of *Natalus* are known: *N. jamaicensis, N. lanatus, N. macrourus, N. major, N. mexicanus, N. primus, N. stramineus* and *N. tumidirostris* (Tejedor, 2011). In South America, south of the Amazon River, only the species *N. macrourus* (formerly known as *N. espiritosantensis*) is known to occur, in Bolivia, Brazil and Paraguay (Tejedor, 2011; Garbino & Tejedor, 2012). *Natalus macrourus* is categorized as Near Threatened on the IUCN Red List (Tejedor & Davalos, 2016) but it is one of the six bat species officially designated as threatened in Brazil, where it is categorized as Vulnerable on the basis of a projected population reduction associated with a decline in its area of occupancy, extent of occurrence and/or quality of habitat (criterion A3c; MMA, 2014). Although *N. macrourus* has a larger distribution than other congeneric species, records are rare within its range (Tejedor, 2011), and there is still a paucity of knowledge about its biology, ecology and natural history.

In this study we (1) addressed gaps in the known distribution of *N. macrourus* in Brazil, obtaining new records for the north-eastern region, (2) updated data on the distribution of the species in Brazil, (3) used these data together with climate and environmental modelling to generate a refined map of the potential distribution of the species in Brazil, (4) analysed pressures on and threats to the species, and (5) assessed its conservation needs.

Methods

Current and potential distribution

We reviewed the available records of *N. macrourus* in Brazil by searching the scientific literature for the key words *Natalus* and Natalidae in Web of Science (2015) and Google Scholar (2015). In addition, we searched for records in the databases of the Chico Mendes Institute for Biodiversity Conservation (ICMBio, 2016), speciesLink (2015), VertNet (2015) and the Global Biodiversity Information Facility (GBIF, 2015; Supplementary Table S1).

The records obtained from the literature were converted into points of occurrence and used to model the potential distribution of *N. macrourus* in Brazil (Supplementary Table S1). Each record was checked and filtered for mistakes in location and/or taxonomy (Peterson et al., 2011). Points that are too close and under the same environmental conditions can bias the modelling as a result of so-called spatial autocorrelation (Boria et al., 2014). To reduce the inherent geographical biases associated with collection data and avoid spatial autocorrelation problems, we produced a map of environmental heterogeneity, using the bioclimatic variables available from WorldClim (2015), and removed records that were within 25 km of one another under the same environmental conditions, keeping the maximum possible number of localities. This resulted in 50 single localities.

Using *MaxEnt* (Phillips et al., 2006), we generated various distribution models for *N. macrourus*, based on two sets of variables at 1 km^2 resolution. To avoid collinearity among bioclimatic variables (i.e. when two variables are highly correlated) we calculated Pearson correlations for the 22 variables available in the WorldClim database and, for those with $\geq$ 80% correlation, eliminated the one with the lowest contribution. Following this selection, for the first set of variables we considered nine bioclimatic variables derived from temperature and rainfall (mean daily temperature range, isothermality, temperature seasonality, maximum temperature in the warmest month, mean temperature in the wettest quarter, mean temperature in the coldest quarter, annual rainfall, rainfall in the driest quarter, rainfall in the warmest quarter). In the second set we considered the same nine bioclimatic variables plus altitude, the normalized difference vegetation index (a proxy for measuring vegetation cover) and a categorical variable of the potential occurrence of caves in Brazil, produced by the National Centre for Cave Research. The shapefile for the potential occurrence of caves in Brazil was produced using data on the location of the main karst regions of Brazil, the geological map of the country, georeferenced records of caves in the database of the National Centre for Cave Research, and the main lithological formations of the caves. We used this approach because *N. macrourus* is generally regarded as a cave-dwelling species (Tejedor & Davalos, 2016). Considering that only a small fraction of Brazilian caves are known, we adopted potential occurrence as a proxy for cave existence in a given area. The National Centre for Cave Research categorizes the potential of cave occurrence in Brazil as unlikely, low, medium, high and very high. In our analysis we scored these categories 0–4, and used the scores to refine the modelling of the potential distribution of *N. macrourus*.

We conducted various tests to find the best parametrization for *MaxEnt* (Radosavljevic & Anderson, 2014). We set the program to use 80% of the data to calibrate the model and 20% for the test, using $n - 1$ replicates, where n is the number of records of occurrence, as suggested by Pearson et al. (2007). To assess the predictive capacity of the models we used the area under the curve (AUC); the best-performing models had AUC values close to 1, whereas AUC values close to 0.5 indicated models were equal to or worse than random (Phillips & Dudík, 2008).

Conservation scenarios for the species

To mitigate the occurrence of false positives (commission errors), the potential distribution generated included a buffer of 300 km around the minimum convex polygon produced with known points of occurrence. Considering the minimum training presence threshold (i.e. the lowest predicted value associated with any one of the observed presence records; Peterson et al., 2011; Radosavljevic & Anderson, 2014), our analysis indicated 18% as the threshold for the presence of *Natalus*. Therefore, we categorized the potential distribution according to occurrence probability: very low ($<$ 18%), low (18–25%), medium (26–50%), high (51–75%) and very high ($>$ 75%). We overlapped the potential distribution generated with three other datasets: (1) deforested areas in Brazil until 2009 (SISCOM, 2015), (2) potential occurrence of caves (CECAV, 2015), and (3) boundaries of fully protected areas as of 2011 (MMA, 2016). This overlap facilitated the calculation of the area of occupation of the species, the number of potential roosts within that area, and the occurrence distribution within protected areas. We also calculated the percentage of caves within the range of the species in habitat remnants for the entire country and for the north-eastern region, and the percentage of caves potentially under pressure from mining activities (DNPM, 2015) and wind farms (ANEEL, 2015).

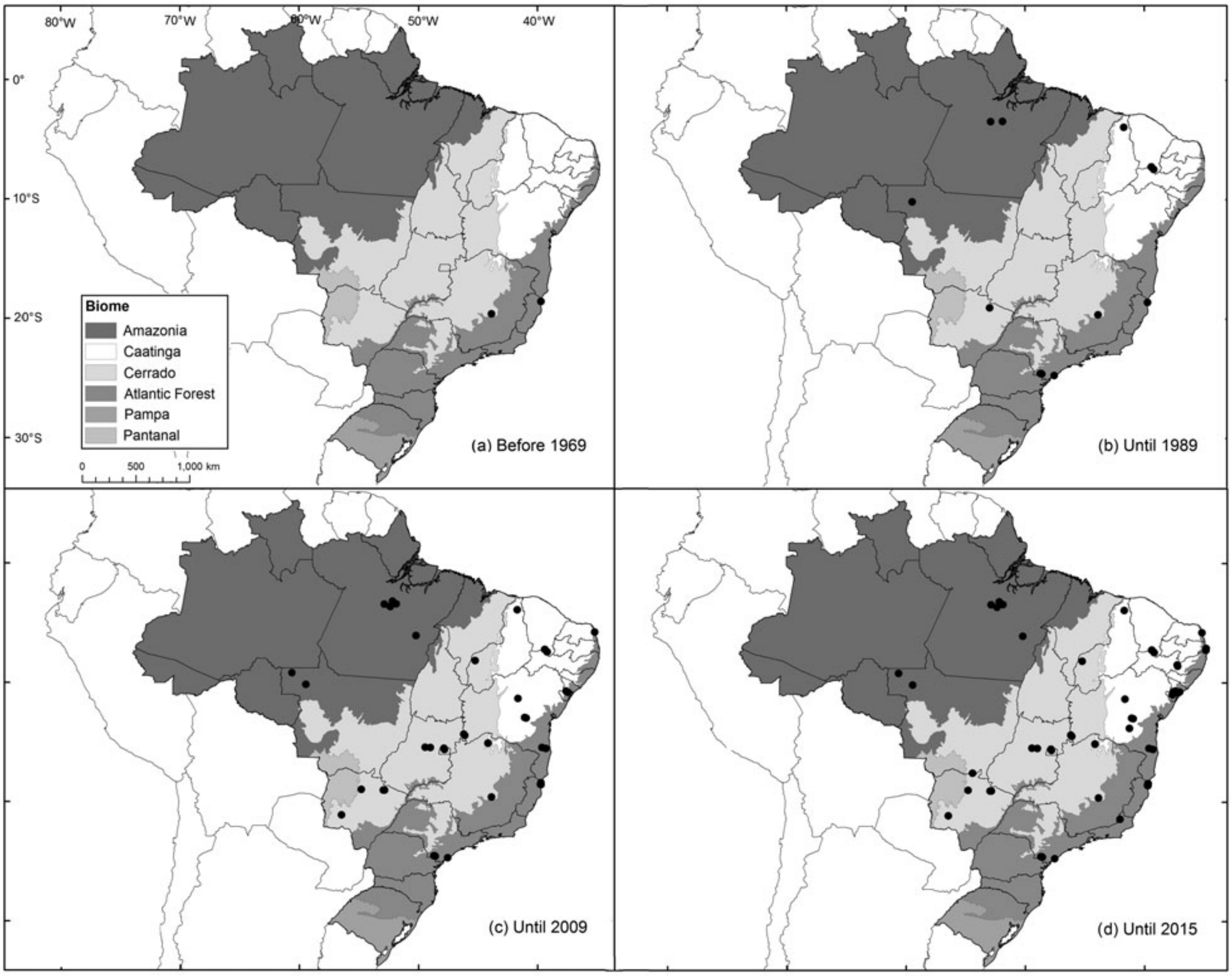

FIG. 1 Spatial evolution of records of the Brazilian funnel-eared bat *Natalus macrourus* (Natalidae) from 1893 to 2015.

Results

Known and new records

Our literature survey yielded 81 records of *N. macrourus* in Brazil (Fig. 1; Supplementary Table S1). We added new records for the north-eastern state of Pernambuco, obtained from captures made during a bat inventory in the cave Meu Rei in Catimbau National Park (62,292 ha), which is located within the Caatinga biome (ICMBio, 2015). The cave is within a sandstone formation, with a horizontal length of 162 m (Azevedo & Bernard, 2015). It harbours a bat community that includes at least seven other species of two families (Phyllostomidae: *Diphylla ecaudata, Carollia perspicillata, Glossophaga soricina, Anoura geoffroyi, Lonchorhina aurita, Tonatia bidens*; and Mormoopidae: *Pteronotus gymnonotus*), which at certain times can surpass 120,000 individuals, most of them *P. gymnonotus*. Measurements in two chambers of the cave, one in its central part and the other in a deeper part, yielded mean temperatures of 25 and 28°C, and relative humidity of 80 and 87%, respectively. The cave is a high priority for full protection (Azevedo & Bernard, 2015).

Using hand nets we captured eight *N. macrourus* (4 males and 4 females) in the cave Meu Rei. The captures were made in October and December 2014, and March, May, June, August and October 2015. Three of these individuals were collected; the others were not marked, so recaptures were possible. We weighed and measured each bat and estimated its age and reproductive status, but retained only the first individual as a voucher, which we deposited in the Mammal Collection of the Federal University of Pernambuco (UFPE 3317; ICMBio/MMA permit #43816-1; Ethics Committee on Animal Care—UFPE #23076.027916/2015-13). All the other bats were released at the site of capture. We recorded another individual of *N. macrourus* on 14 May 2015 during a visit to another cave 11 km away, outside the limits of Catimbau National Park.

The records from Pernambuco were added to the existing records of the species in Brazil for 1893–2015 (Fig. 2). Sixty percent of these records are from caves, grottos or within 5 km of known caves, and 70% are from within 10 km of known caves. Thirty percent of all records are from ecotones between savannah, steppic savanna, dry coastal vegetation

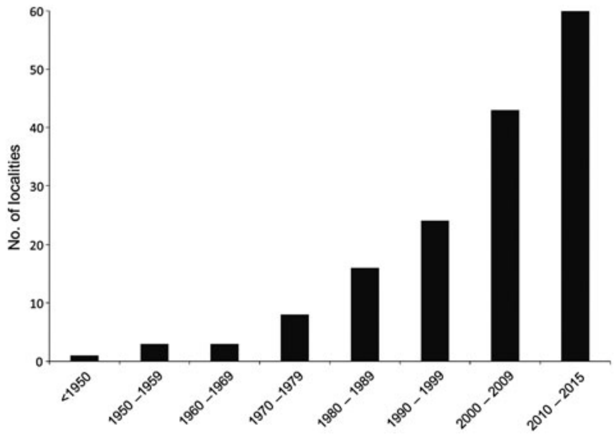

FIG. 2 Temporal evolution of the number of localities with known records of the Brazilian funnel-eared bat in Brazil from 1893 to 2015.

(restinga), or croplands, 25% are from dense rainforests, and 20% are from savannahs. The records are broadly distributed and occupy four of the six Brazilian biomes (Fig. 1). Most records are from Atlantic Forest (40%), followed by Cerrado (23%), Amazonia (17%) and Caatinga (16%). In 2015 *N. macrourus* was included in the species list for the Pantanal, based on records in the state of Mato Grosso do Sul (Fischer et al., 2015).

Potential distribution modelling

The potential distribution of *N. macrourus* modelled using bioclimatic variables combined with the potential occurrence of caves was 4,445,996 km² ($AUC_{training} = 0.89 \pm SD\ 0.01$; $AUC_{test} = 0.87 \pm SD\ 0.05$), which is 11.5% smaller than the potential distribution modelled using bioclimatic variables only, which was 5,024,815 km² ($AUC_{training} = 0.86 \pm SD\ 0.01$; $AUC_{test} = 0.85 \pm SD\ 0.04$). However, considering the potential distribution based on both bioclimatic variables and the potential occurrence of caves there was a reduction of 26% in the areas of highest environmental suitability (> 75%) for the species when compared with the model based on bioclimatic variables only. Our model suggests that *N. macrourus* is positively associated with areas where there is a high potential occurrence of caves, and negatively associated with areas with high variation in mean daily temperature and mean annual rainfall.

The areas of highest environmental suitability for *N. macrourus* corresponded to only 3% of the total area of potential distribution, and these areas were within the Caatinga and Atlantic Forest biomes, mostly in the north-eastern region. That region alone comprised 67% of the total area of highest environmental suitability in the model that included the potential occurrence of caves, and 92% in the model with bioclimatic variables alone (Fig. 3). In the Atlantic Forest, the areas of highest environmental suitability were located in Sergipe, Alagoas, eastern Bahia, and mid-eastern Pernambuco and Paraíba states. Additionally, the areas of high environmental suitability (50–75%) accounted for < 20% of the total area modelled, and were located mostly in the Atlantic Forest of north-eastern Brazil (55% in the model including the potential cave occurrence variable; 46% without). Areas of low environmental suitability (18–25%) were found in north-western Bahia, southern Piauí and eastern Amazonas (to the south of the Amazon River) states, as well as in mid-northern Mato Grosso, Tocantins and Paraná states.

Conservation scenarios for the species

Based on the model of potential distribution of the species, considering the importance of caves for *N. macrourus* and considering the area where original vegetation cover was already lost, we estimate that the species has already lost 54% of its habitat in Brazil and that there are < 35% of habitat remnants in areas with the highest environmental suitability (Fig. 3). We estimate that 53% of the caves recorded within the distribution of *N. macrourus* are in habitat remnants and c. 54% are < 5 km from mining operations. Furthermore, 2% of these caves are < 10 km from wind farms, and only 4% of the potential distribution of *N. macrourus* is located within fully protected areas.

Approximately 30% of the area of potential distribution of *N. macrourus* is located in north-eastern Brazil, where 44% of the caves are in human-modified areas. We estimate that *N. macrourus* has already lost 50% of its natural habitat in north-eastern Brazil, and up to 65% in areas of highest environmental suitability in the eastern part of the region, where human population growth is higher. In that region only 2% of the potential distribution of *N. macrourus* is located within fully protected areas.

Discussion

The records of *N. macrourus* indicate a broad distribution in Brazil, with the species occurring from xeric (e.g. the Caatinga, with annual rainfall < 800 mm) to moist habitats (e.g. the Amazon, with annual rainfall > 2,000 mm; Tejedor, 2011). However, although our model suggests a large potential distribution, most of the records in Brazil are from areas of open vegetation, and our models suggest a preference for areas with low mean annual rainfall, lower variation in daily temperature, and high cave occurrence potential. These preferences may significantly restrict the effective area of occurrence of *N. macrourus*. We observed that only 3% of the total area of potential distribution has high environmental suitability for the species, and is located in the Caatinga and Atlantic Forest, mostly in north-eastern Brazil.

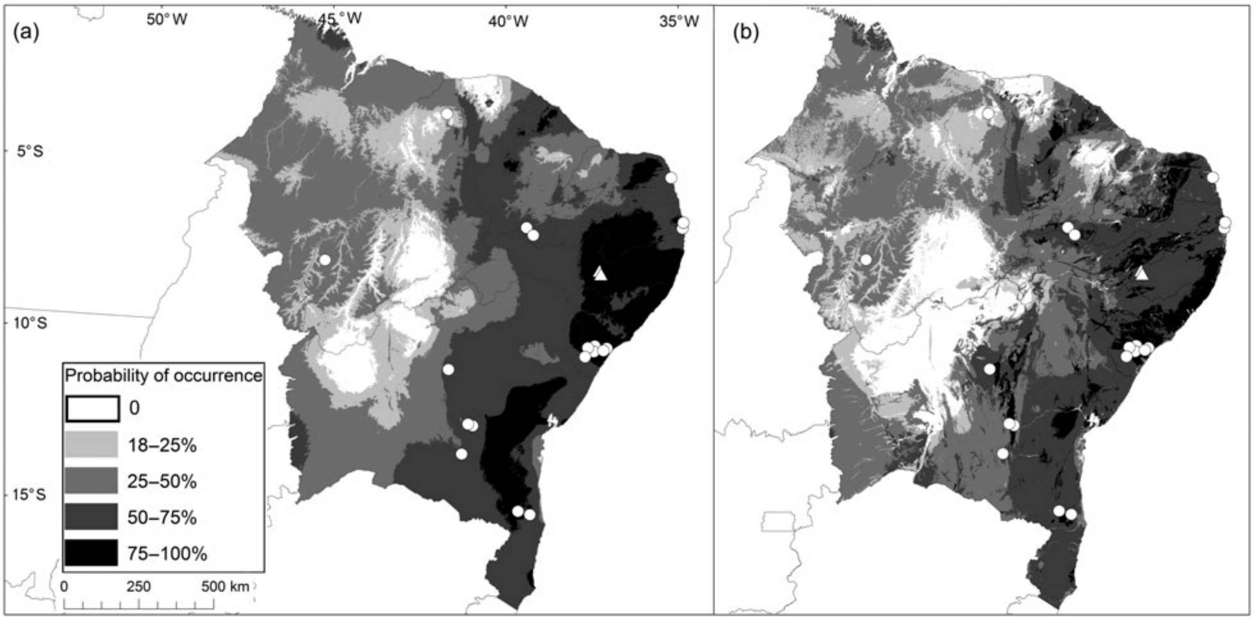

FIG. 3 Potential distribution of the funnel-eared bat *N. macrourus* in north-eastern Brazil, modelled considering only bioclimatic variables (a), and with the addition of cave occurrence potential (b). White circles represent known records for the species, and white triangles represent new records for the state of Pernambuco.

Brazil may have > 310,000 caves (Piló & Auler, 2011) but < 5% of them have been officially recorded (ICMBio/CECAV, 2016). Species of the genus *Natalus* are considered to be dependent on caves for roosting (Taddei & Uieda, 2001; Tejedor et al., 2004; Tejedor & Davalos, 2016), and our analysis confirms this strong association. This finding is a cause for concern, as changes in the Brazilian cave protection law have increased the vulnerability of cave environments and may result in a poor outlook for the conservation of cave-dependent species. Until 2008, Brazilian caves were fully protected. However, the law was changed by Presidential Decree no. 6,640, which determined that caves should be categorized according to their relevance, and only those categorized as being of 'maximum relevance' would be fully protected (Brasil, 2008). The prior categorization of all the Brazilian caves as a prerogative for their protection is infeasible and, in practice, the change in the law has reduced their protection, as caves in the categories of high, medium and low relevance may be legally exploited and destroyed. Decree no. 6,640 is therefore considered to be a serious threat to the conservation of Brazilian bats (Bernard et al., 2012). Cave protection is highlighted as being a priority for bat conservation (e.g. Fenton, 1997; Luo et al., 2013; Furey & Racey, 2016) and an increase in the number of formally protected roosts is needed urgently in Brazil, given the pressure on cave environments there (e.g. Ribeiro, 2015).

As well as depending on caves for shelter, *Natalus* bats, which are strictly insectivorous, also depend on having tracts of habitat of sufficient environmental quality available for foraging. Therefore, *N. macrourus* may face other pressures in addition to roost loss. Our results suggest that c. 54% of the known caves within the potential distribution of *N. macrourus* are < 5 km from mining areas. Besides the direct loss of shelters caused by the exploration of caves for mining, explosives frequently used in that process, the presence of people, and the noise caused by machinery can affect bats using these shelters (Furey & Racey, 2016). Furthermore, 2% of these caves are < 10 km from wind farms, which are another threat to bats (Barclay et al., 2007; Arnett et al., 2008). The catchment areas of wind farms in the Neotropics are largely unknown but studies in Europe and Canada have found that wind turbines influence not only bat populations in close proximity but also those at distances of several hundreds of kilometers or even > 1,000 km (Voigt et al., 2012; Baerwald et al., 2014). We recommend that caves with confirmed occurrence of *N. macrourus* close to mines or wind farms should be protected and monitored in the medium and long term.

The conservation outlook for *N. macrourus* would be more positive if there were a larger number of protected areas within its distribution. However, only 4% of the potential distribution of *N. macrourus* is located within fully protected areas. In the north-eastern region, which has the greatest potential occurrence of *N. macrourus*, the percentage is even lower (2%). Hence, a scenario in which low roost protection is combined with other threats, such as mining and habitat loss, degradation and fragmentation, could extirpate some populations locally (Tejedor, 2011).

Natalus spp. are frequently associated with several other bat species (Ruschi, 1951; Trajano & Moreira, 1991; Trajano & Gimenez, 1998; Gregorin & Mendes, 1999; Taddei &

Uieda, 2001). We observed *N. macrourus* roosting with *A. geoffroyi, C. perspicillata, D. ecaudata, G. soricina, L. aurita, P. gymnonotus* and *T. bidens; L. aurita* is also categorized as Vulnerable in Brazil. Hence, protecting the caves used by *N. macrourus* could also conserve other species of bats as well as the rich, highly specialized and frequently endemic cave biota (Furey & Racey, 2016).

Robust databases of species records are necessary for improving potential distribution models in large and undersampled countries, such as Brazil (e.g. Oliveira et al., 2016), which would, in turn, highlight priority areas for inventories and conservation (Costa et al., 2010; Moreira et al., 2014; Ingberman et al., 2016). However, species distribution models are influenced by many factors, such as spatial resolution, environmental variables and the quality of distribution records. The addition of new records can produce distinct modelling outputs, and models based on partial datasets for species occurrence can lead conservationists or decision makers to incorrect conclusions (Aguiar et al., 2016).

There are no formal records of bats for almost 60% of Brazil (Bernard et al., 2011) and there is limited knowledge of the distribution of several bat species in the country. New records, such as those reported here from Pernambuco, help to reduce these gaps for poorly known, hard to capture species, such as *Natalus* spp. The previous records closest to Pernambuco were from Ceará, Sergipe and Paraíba states, >235 km from our study area (Taddei & Uieda, 2001; Rocha et al., 2013). Moreover, nearly half of the 81 records of occurrence of *N. macrourus* in Brazil have been gathered since 2000 (Fig. 1; Leal et al., 2012), indicating that recent efforts have resulted in a significant refinement of the species' distribution. Considering the high potential occurrence of caves in north-eastern Brazil (Jansen et al., 2012), and considering that at least three (*N. macrourus, L. aurita* and *Furipterus horrens*) of the six threatened bat species in Brazil are frequent or exclusive cave users, caves in north-eastern Brazil are a priority for bat inventories so that roosts used by *Natalus* or any other threatened bat species can be identified and proposed for full protection.

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Author contributions

M. Delgado-Jaramillo collected data and conducted the analysis. E. Barbier collected data. E. Bernard conceived the research. All authors contributed to writing the article.

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