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RESEARCH ARTICLE

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# Playback point counts and N-mixture models suggest higher than expected abundance of the critically endangered blond titi monkey in northeastern Brazil

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## Abstract

Effective management of threatened species requires accurate population size estimation and monitoring. However, reliable population size estimates are lacking for many endangered species. The critically endangered blond titi monkey (*Callicebus barbarabrownae*) is an endemic primate of the Caatinga biome in Northeastern Brazil. A previous assessment based on presence-only data estimated a minimum population size of 260 mature individuals in 2,636 $km^2$, and studies based on visual records suggested very low local relative abundance. However, this cryptic species is known to be difficult to visually detect. We played back recordings of *C. barbarabrownae* loud calls to count the number of responding groups in 34 sampling sites during 9 consecutive days in a 221-$km^2$ study area. Repeated group counts at sites were used in N-mixture models, which account for imperfect detection, to estimate the number of groups in relation to dry forest area and distance to villages. We estimated a total of 91 groups in the study area. Considering the mean number of adults per group as three, we estimated a population of 273 adult individuals, resulting in a density of 2.3 individuals/$km^2$ in the dry forest habitat. Detection probability was four times higher for surveys conducted between sunrise to midmorning than between midmorning to sunset. We also found that *C. barbarabrownae* abundance increases with increasing dry forest area and increasing distance to the nearest village, indicating the need to promote dry forest restoration in the Caatinga. As our results suggest a larger population of *C. barbarabrownae* than had been previously estimated for its entire distribution, our results suggest a need for similar assessments in other areas to reliably estimate the total population size. This study demonstrates how playback surveys coupled with N-mixture models can be used to estimate population sizes of acoustically-responsive primates, and thus contribute to more effective conservation management.

KEYWORDS

Caatinga, *Callicebus barbarabrownae*, dry forest, endangered species, imperfect detection, IUCN Red List

  

## 1 | INTRODUCTION

Conservation status assessment and effective management of threatened species require accurate population estimates and monitoring. Attaining reliable abundance estimates strongly depends on sampling design, method detection capacity, and appropriate data analysis to deal with spatial variation and survey error (Williams, Nichols, & Conroy, 2002; Yoccoz, Nichols, & Boulinier, 2001). Although sampling and analytical methods have improved in recent decades (Dénes, Silveira, & Beissinger, 2015; Elphick, 2008; Guillera-Arroita, 2017), accurate population estimates are still lacking for most species, including endangered primates. While 60% of primate species are threatened with extinction and 75% are facing population decline, data for most species are still limited and there is an urgent need to generate information about population sizes (Estrada et al., 2017).

The blond titi monkey (*Callicebus barbarabrownae*) is the unique endemic primate of the Caatinga biome in Northeastern Brazil. It is categorized as Critically Endangered (Printes, Alonso, & Jerusalinsky, 2018; Veiga et al., 2008) by the criteria C2a(i): the population size is estimated to number fewer than 250 adult individuals, the population is experiencing a continuous decline, and no subpopulation is estimated to contain more than 50 adult individuals (IUCN, 2012). Two local population assessments based on visual surveys concluded that the species occurs in extremely low abundance (Corsini & Moura, 2014; Freitas, De-Carvalho, & Ferrari, 2011), and Printes, Rylands, and Bicca-Marques (2011) estimated a minimum population of 260 individuals in the species' range of 2,636 $km^2$.

Titi monkeys (subfamily Callicebinae; Byrne et al., 2016) are recognized as cryptic and shy, living in small groups often including a pair of adults and 1–3 offspring (Bicca-Marques & Heymann, 2013). Groups are territorial, have small home ranges (from 0.01 $km^2$ to 0.48 $km^2$) and small daily path lengths (mean often about 600–700 m; Bicca-Marques & Heymann, 2013). Titi monkeys are difficult to visually detect but respond vocally to playback calls (Dacier, Luna, Fernandez-Duque, & Di Fiore, 2011; Gestich, Caselly, Nagy-Reis, Setz, & Cunha, 2017), as titi groups often emit loud calls for intergroup communication (Caselli, Mennill, Bicca-Marques, & Setz, 2014; Kinzey & Robinson, 1983). Active acoustic methods are therefore more effective than visual surveys in detecting their presence (Corsini & Moura, 2014; Dacier et al., 2011).

Studies have used acoustic playback methods to determine titi monkeys' presence (Jerusalinsky et al., 2006; Marques, Beltrão-Mendes, & Ferrari, 2013; Printes et al., 2011), and Gestich et al. (2017) described a protocol to assess primate densities using playbacks. However, presence-only data can poorly estimate abundance (Dénes et al., 2015; Guillera-Arroita, 2017) and the protocol developed by Gestich et al. assumes perfect detection and underestimates abundance (Kellner & Swihart, 2014). Distance sampling with playback has been used to estimate titi monkeys' population density, but it requires accurately estimating the distance from the observer to the animal, which is challenging in acoustic surveys (Dacier et al., 2011). N-mixture models had been developed to estimate the abundance of unmarked species considering imperfect detection (Royle, 2004), and recently have been used to estimate the number of Old World monkey groups in Tanzania (Rovero et al., 2015).

Here, we aim to estimate the abundance of the critically endangered blond titi monkey in a 221-$km^2$ area, using repeated playback point count surveys, and N-mixture models to account for detectability. We tested the hypotheses that the number of blond titi monkey groups increases with increasing dry forest area and distance from villages. We estimated the population size by the number of groups predicted using N-mixture modeling for the study area multiplied by the mean number of adults known for blond titi monkey groups.

## 2 | METHODS

### 2.1 | Study area

The Caatinga biome is a seasonally dry tropical forest and woodland in Brazil. The regional climate is semiarid, with low precipitation/potential evapotranspiration rate. Most of the rainfall is concentrated, and droughts are frequent. Our study was conducted in a 221-$km^2$ area in Boa Vista do Tupim municipality (12°28′–12°36′S, 40°34′–40°41′W), in Bahia State (Figure 1). Seasonally dry forest, the main habitat of *C. barbarabrownae*, covers 52% of the study area and the remaining 48% is covered by pasture, shrubs, and villages. The mean annual precipitation from 2010 to 2018 was 526 mm, and the total precipitation in 2017 was 410 mm, concentrated in April (85 mm) and November–December (150 mm). The mean annual temperature is 24°C, ranging from 16°C to 30°C (INMET, 2019).

### 2.2 | Playback survey

We surveyed 34 sampling sites (Figure 1) for *C. barbarabrownae* groups during 9 consecutive sampling occasions (days), from December 2, 2017 to December 10, 2017. A short period of study is important to deal with the assumption of population closure (see Section 2.3). We sampled during the rainy season because blond titi monkeys are known by local people to call more often this period. Each sampling site was defined as a 2.6-$km^2$ hexagon (1 km per side) centered on a count point (Figure 2), because while blond titi monkeys typically respond to playbacks within 500 m, responses from up to 1 km away have been recorded (A. C. Alonso, personal communication, December 2017). Considering the largest home range known for titi monkeys (0.48 $km^2$; Bicca-Marques & Heymann, 2013), one sampling site could contain five nonoverlapping groups.

We selected sites opportunistically, based on accessibility by roads and trails in the study area (Figure 1). We do not recommend such a convenience sampling design and suggest Smith, Anderson, and Pawley (2017) and Thompson (2012) to design a probability sample in future studies, to ensure independent and representative sampling units. Since many sites partially overlapped (Figure 1), we carefully avoided counting groups twice on the same day using the strategy depicted in Figure 2.

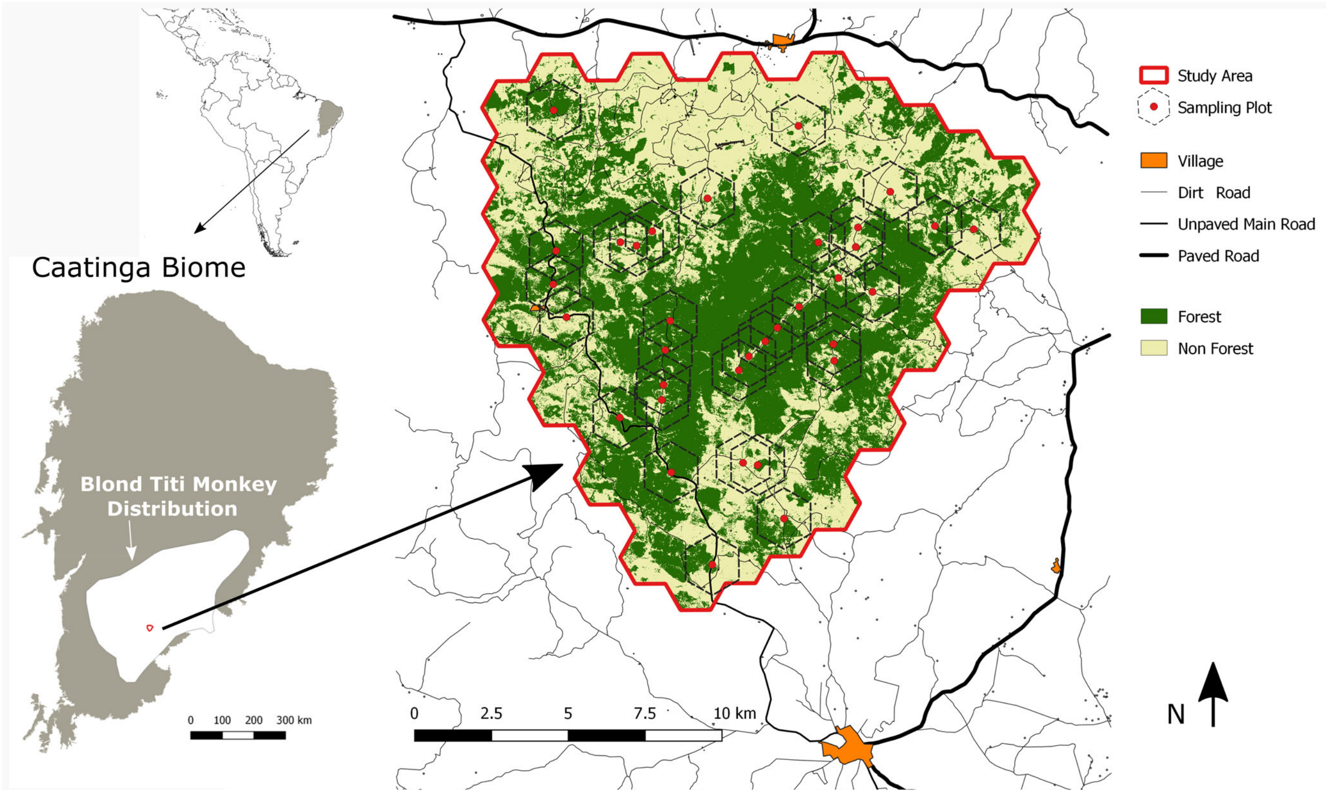


**FIGURE 1** Distribution of the blond titi monkey (*Callicebus barbarabrownae*) and location of the study area in the Caatinga biome, Brazil. We estimated *C. barbarabrownae* abundance in the study area from playback point count surveys conducted in 34 2.6-km$^2$ sampling sites, modeling the number of groups as a function of the forest area in sampling sites and site distance to the nearest village

We surveyed each site 1–9 times during the study. Temporal replicates of observations were used to estimate detection at each site (see Section 2.3). We used a megaphone (CSR Professional Megaphone SK66 25 W) to play a 1.5-min group loud call, followed by a 4-min listening period, three times during each site survey (total 16.5 min survey). We used one duet recording performed by free-ranging *C. barbarabrownae* in Caatinga dry forest, 380 km from the study area. We played back the call around 100 dB measured at one meter from the megaphone, to keep similar call volume in all samplings. Two observers, approximately 50 m apart, counted the number of different groups calling during each survey. We estimated group locations using call directions recorded by each observer with a compass (Figure 2). Observers kept visual contact to agree on each group call direction. Considering titi monkey small home ranges, we are confident that we had no situation of group double counts during any sampling occasion. We varied survey time from sunrise (5:05 a.m.) to sunset (5:50 p.m.), starting from a different site each day (File S1). As titi monkeys call more often in the morning (Corsini & Moura, 2014; Price & Piedade, 2001), we included survey time as a predictor of detection in our models (two classes: Sunrise to midmorning, from 5:05 a.m. to 9:59 a.m. and midmorning to sunset, from 10:00 a.m. to 5:50 p.m.).

We included the dry forest area in the sampling site and site distance to nearest village as predictors of *C. barbarabrownae* group abundance (Table 1). We predicted that group abundance would be positively related to dry forest area and distance from the nearest village since blond titi monkeys avoid people and may be hunted in the region. Villagers regularly use forested areas for hunting, gathering, and cattle raising.

We created a two-class land cover map of the study area (forest X non-forest; Figure 1) by classifying a 2017 Google Earth image with the HistMapR v0.1 package (Auffret et al., 2017) in R version 3.5.0 (R Core Team, 2018). We classified the map based on color RGB values for 50 ground samples of each land class. To evaluate classification accuracy, we used a confusion matrix of 50 random samples of each class taken from the classified map and compared it to the class in the Google Earth image. A Google Earth image can be considered a good approximation of truth because forest X non-forest color is very easy to differentiate in the region. Our map had an overall accuracy of 91%: 95% of pixels identified as Forest were actually a forest, and 89% of pixels identified as non-forest were actually non-forest (user's accuracy).

We measured forest area in each 2.6-km$^2$ sampling site ($n$ = 34) with Fragstats version 4 (McGarigal, Cushman & Ene, 2012). Distance to the nearest village was measured from the count point in the center of each sampling site with QGIS (QGIS Development Team, 2018). To estimate group abundance for the entire study area from our sample of 34 sites, we partitioned the 221-km$^2$ study area into a grid of nonoverlapping 2.6-km$^2$ hexagons and measured forest area and distance to the nearest village for each hexagon ($n$ = 85; Figure 3).

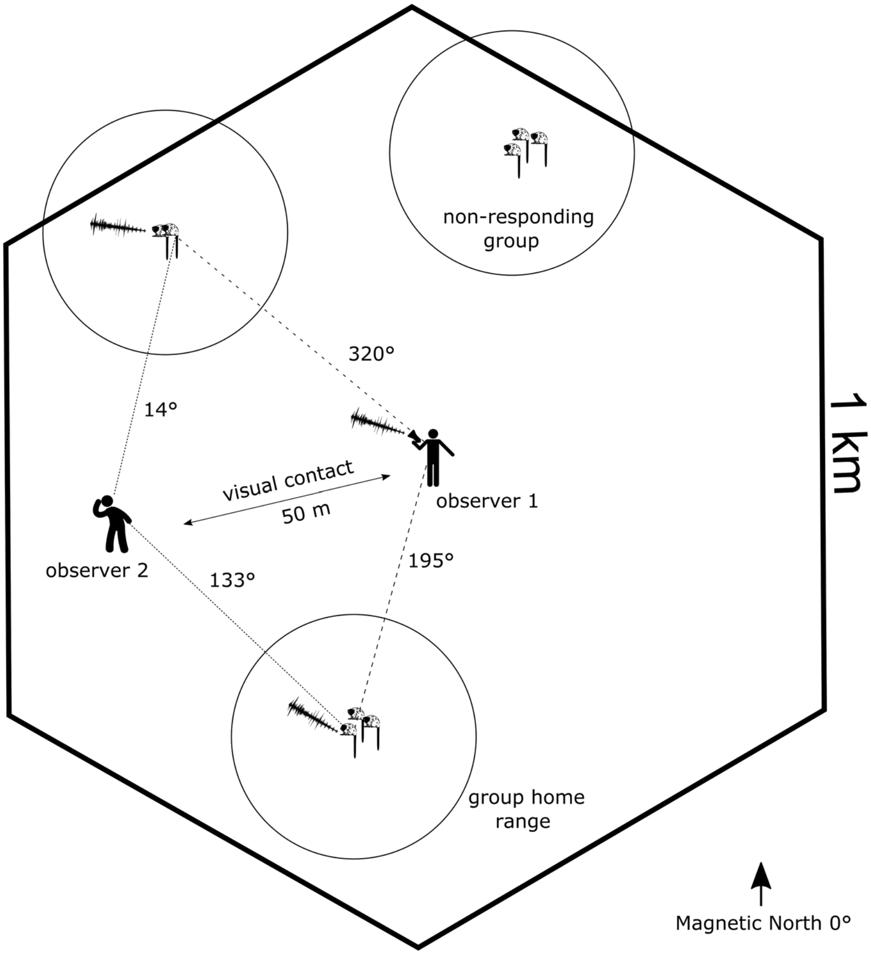


**FIGURE 2** Playback point count survey for blond titi monkeys in the hexagonal sampling site (1 km side, 2.6 $km^2$). Locations of responsive groups were determined by the intersection of two bearings taken from two observers 50 m apart

## 2.3 | Data analysis

Data on species abundance is virtually always prone to survey errors, namely false negatives (no detection of individuals, or groups of individuals as in this study, that exist in the area of observation; so-called imperfect detection) and false positives (detection of individuals, or groups, that do not exist in the area of observation). In the last decades, hierarchical modeling emerged in ecological literature to account for survey errors in analyses of species occurrence, abundance, and richness (Guillera-Arroita, 2017; Kéry & Royle, 2016), though most refereed papers still fail to account for survey error (Kellner & Swihart, 2014).

We estimated the abundance and detection probability of *C. barbarabrownae* groups with binomial N-mixture hierarchical models (Royle, 2004). A hierarchical model is a coupled set of models that are conditionally related to each other, where a random variable present in a given submodel depends on parameters estimated in a lower level submodel (Kéry & Royle, 2016). Usually, hierarchical models present one submodel for the observational process (data) and one submodel for the state process (e.g., the ecological process of interest, abundance in our case). In the binomial N-mixture models it is assumed the population being sampled is closed with respect to mortality, recruitment, and movement so that the counts may be viewed as binomial random variables (Royle, 2004). A lower level submodel considers our data (count history of blond titi monkey groups; Table 1) as an outcome of a binomial distribution and depending on the detection probability ($p$) and the abundance of groups at site $i$ ($N_i$). Detection probability is estimated from the variation of counts at sites $i$ on different occasions $j$. In the submodel describing abundance, the number of groups at site $i$ ($N_i$) comes from a Poisson distribution and depends on $\lambda$, the mean abundance over all sites (sampled or not). Sampling site differences in the number of observations are accounted by N-mixture models, the number of observations affecting the precision of detection and abundance estimates at each site.

We used the "pcount" function from the R package unmarked v0.13-0 (Fiske & Chandler, 2011) to estimate model parameters by maximum likelihood. We adopted multimodel inference (Burnham & Anderson, 2002; Symonds & Moussalli, 2011), and performed model selection using Akaike's information criterion corrected for small sample sizes (AICc) to rank competing models using the R package AICcmodavg v2.1-1 (Mazerolle, 2017). We first tested the effect of survey time on detection by competing a null (intercept-only) model with a model including survey time class as a predictor of detection. As the latter had a lower AICc (Table 2), we used survey time as a predictor of detection in all subsequent modeling. We then included in the set of competing models those containing forest area, distance to the nearest village, and both as predictors of *C. barbarabrownae* group abundance.

**TABLE 1** Number of blond titi monkey groups recorded by playback response at 34 sites (2.6 $km^2$) during nine consecutive sampling days in Boa Vista do Tupim, Brazil

| | Number of blond titi monkey groups recorded | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling sites | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 | Day 7 | Day 8 | Day 9 | Forest area ($km^2$) | Distance to village (m) |
| 1 | ND | ND | 0 | 0 | 0 | ND | 0 | ND | ND | 1.47 | 5821.1 |
| 2 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 2.06 | 6896.4 |
| 3 | ND | 1 | 0 | 1 | 0 | 1 | 1 | 0 | ND | 1.64 | 6707.9 |
| 4 | ND | 0 | 0 | 0 | 0 | 1 | 0 | 0 | ND | 1.93 | 4329 |
| 5 | ND | 0 | 0 | 0 | 0 | 3 | 0 | 0 | ND | 1.37 | 4997.6 |
| 6 | ND | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1.44 | 5632.9 |
| 7 | ND | 2 | 1 | 3 | 0 | 2 | 1 | 1 | 0 | 2.14 | 5780.7 |
| 8 | ND | 1 | 0 | 2 | 0 | 2 | 1 | 0 | 0 | 2.42 | 6199 |
| 9 | ND | 1 | 1 | 2 | 0 | 1 | 0 | 0 | 0 | 2.40 | 6543.7 |
| 10 | ND | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 2.12 | 6865.2 |
| 11 | ND | 1 | 0 | 0 | 0 | 0 | 0 | 2 | ND | 1.16 | 5315.1 |
| 12 | ND | 0 | 0 | 0 | 0 | 0 | 0 | ND | ND | 0.87 | 8422 |
| 13 | ND | 0 | 0 | 0 | 0 | 0 | 0 | ND | ND | 1.89 | 1959.5 |
| 14 | ND | 0 | 0 | 0 | 0 | 0 | 0 | ND | ND | 1.66 | 926 |
| 15 | ND | 0 | 0 | 0 | 0 | 0 | 0 | ND | ND | 1.11 | 992.3 |
| 16 | ND | 1 | 1 | ND | 1 | 0 | 1 | ND | 1 | 2.04 | 5029.2 |
| 17 | ND | 0 | 0 | ND | 0 | 0 | 0 | ND | 0 | 2.17 | 4803.4 |
| 18 | ND | 0 | 1 | ND | 1 | 0 | 1 | ND | 0 | 1.60 | 4461.1 |
| 19 | ND | 1 | 0 | 0 | 1 | 3 | 1 | ND | ND | 1.52 | 7205.5 |
| 20 | ND | 0 | ND | 0 | 0 | ND | 0 | 0 | ND | 0.38 | 1855.5 |
| 21 | ND | ND | 0 | ND | 0 | 0 | 0 | ND | 0 | 2.40 | 4383.6 |
| 22 | ND | ND | 1 | ND | 3 | 0 | 1 | ND | 0 | 2.42 | 4342.2 |
| 23 | ND | ND | ND | 0 | ND | ND | ND | ND | ND | 0.86 | 1680.6 |
| 24 | ND | ND | ND | 0 | ND | ND | ND | ND | ND | 1.44 | 3808.3 |
| 25 | ND | ND | ND | 0 | ND | ND | ND | ND | ND | 1.14 | 3813.8 |
| 26 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 0.42 | 5463.7 |
| 27 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 0.75 | 7350.1 |
| 28 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 1.03 | 7691.5 |
| 29 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 0.53 | 8803 |
| 30 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 0.40 | 8375 |
| 31 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 2.07 | 7356.8 |
| 32 | ND | ND | ND | ND | ND | ND | ND | 0 | ND | 1.94 | 7848.4 |
| 33 | ND | ND | ND | ND | ND | ND | 1 | ND | 2 | 2.24 | 6822.9 |
| 34 | ND | ND | ND | ND | ND | 0 | ND | ND | ND | 1.20 | 3449.6 |
| Total | 0 | 10 | 7 | 10 | 6 | 14 | 8 | 5 | 5 | | |

*Note:* Forest area at each site and distance to the nearest village for each site were used as predictors of group abundance in the analysis.
Abbreviation: ND, no data.

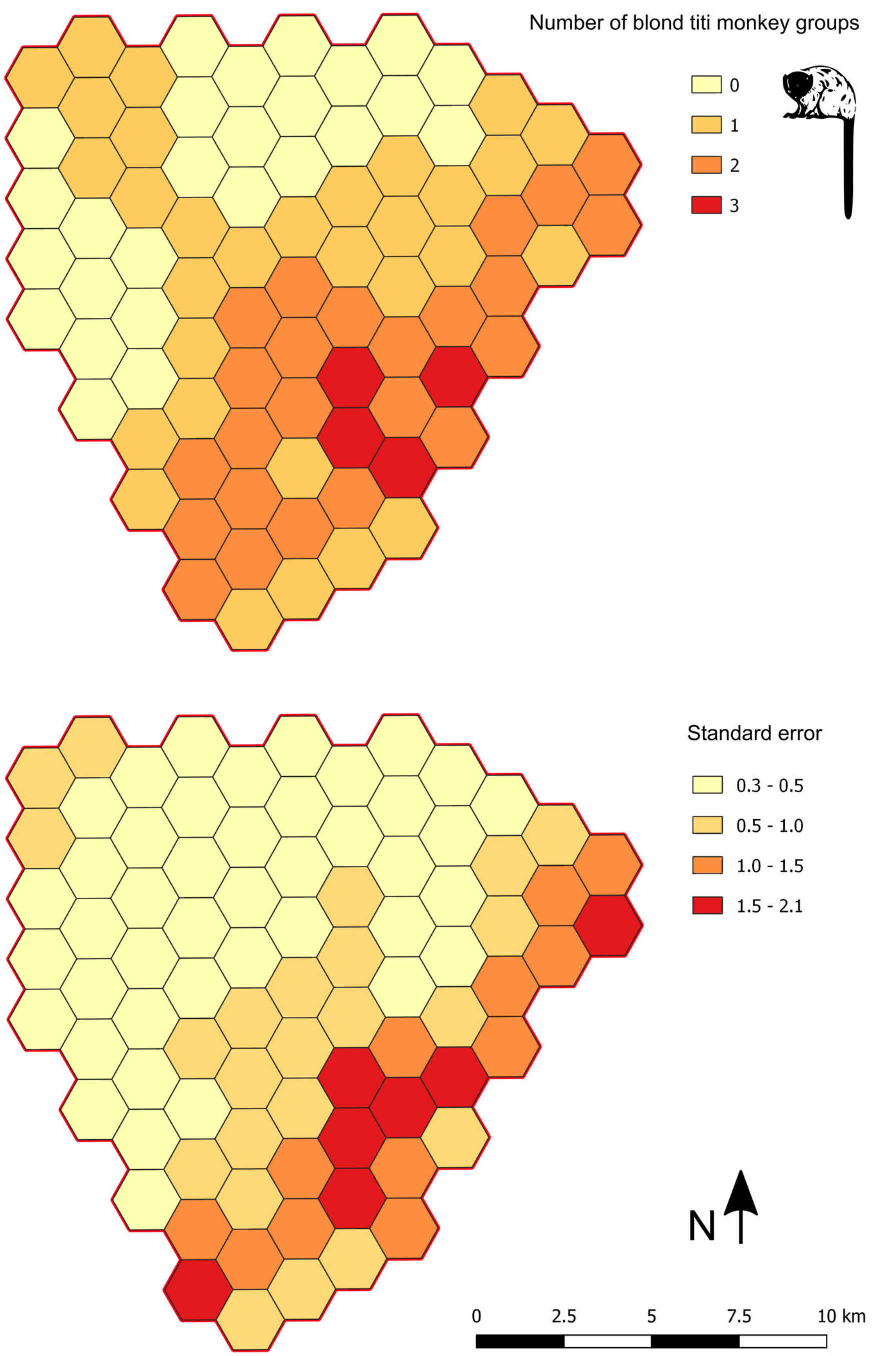


**FIGURE 3** The number of blond titi monkey (*Callicebus barbarabrownae*) groups and standard error estimated by model averaging for 85 2.6-km$^2$ hexagons (1 km per side) covering the study area. Group abundance estimates were calculated using a conservative rounding criterion (see Section 2)

Predictors showed virtually no linear correlation (Pearson's $R$ = .01), and we used standardized ($z$-transformed) values for analysis. We assessed the goodness-of-fit of models by a parametric bootstrap of the $\chi^2$ statistic, using the "fitstats" function in the R package AHMbook v0.1.3 (Kéry, Royle, & Meredith, 2017) and the "parboot" function with 1,000 simulations in unmarked (Fiske & Chandler, 2011).

Competing models showed small differences in AICc (except for the null model; Table 2), so we used model averaging considering all but the null model to obtain estimates. We estimated the number of *C. barbarabrownae* groups in each sampling site and predicted the number of groups in each nonoverlapping hexagon covering the entire study area ($n$ = 85) using the "predict" function from unmarked (Fiske & Chandler, 2011). To estimate the total number of groups in the study area, we adopted a conservative criterion for each hexagon by considering 0–0.8 as 0 groups, 0.81–1.8 as 1 group, 1.81–2.8 as 2 groups, and so on. The same criterion was used to define lower and upper confidence limits for the estimate. We estimated the number of adult blond titi monkeys by multiplying the number of estimated groups by the mean number of adults in *C. barbarabrownae* groups (three adults, ranging from 1 to 6; mode = 4) sighted in the Caatinga (4 groups sighted in this study, three recorded by Corsini & Moura, 2014 and 24 sighted groups by A. C. Alonso, unpublished data).

**TABLE 2** Competing N-mixture models predicting *Callicebus barbarabrownae* group abundance as a function of forest area in 2.6-km$^2$ sampling sites ($n = 34$) and site distance to the nearest village

| Model | Meaning | $K$ | AICc | ΔAICc | $w_i$ | LL | βFA | βDV | βT | GoF test $\chi^2$ (2.5–97.5%) | GoF test $p$ Value | Detection | N groups |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\lambda \sim$ FA + DV, $p \sim T$ | Abundance varies between sites according to the forest area in the site and site distance from villages, detection varies according to time of the survey | 5 | 222.2 | 0 | 0.49 | −105.04 | 0.45 | 0.62 | −2 | 199 (107–205) | .86 | SM = 0.47<br>MS = 0.11 | 88 |
| $\lambda \sim$ DV, $p \sim T$ | Abundance varies between sites according to the site distance from villages, detection varies according to time of the survey | 4 | 223.2 | 0.97 | 0.3 | −106.91 | | 0.53 | −2.1 | 132 (116–206) | .79 | SM = 0.49<br>MS = 0.11 | 117 |
| $\lambda \sim$ FA, $p \sim T$ | Abundance varies between sites according to the forest area in the site, detection varies according to time of the survey | 4 | 224.8 | 2.65 | 0.13 | −107.75 | 0.46 | | −2 | 142 (116–203) | .64 | SM = 0.52<br>MS = 0.12 | 67 |
| $\lambda \sim 1$, $p \sim T$ | Abundance does not vary between sites, detection varies according to time of the survey | 3 | 225.8 | 3.65 | 0.08 | −109.54 | | | −2.1 | 158 (122–208) | .38 | SM = 0.53<br>MS = 0.12 | 85 |
| $\lambda \sim 1$, $p \sim 1$ | Abundance and detection do not vary between sites | 2 | 262.8 | 40.6 | 0 | −129.22 | | | | 201 (122–198) | .01 | 0.18 | 170 |

*Note:* Detection of groups was modeled as a function of survey time (sunrise to midmorning, SM or midmorning to sunset, MS). Standardized coefficients (*β*) for each predictor variable, $\chi^2$ goodness-of-fit test results (GoF test), and detection and the number of blond titi monkey groups in the study area estimated by each model.

Abbreviations: AICc, Akaike's information criterion corrected for small sample size; DV, sampling site distance to the nearest village; FA, forest area in sampling sites; *K*, number of estimable parameters; LL, log-likelihood; *p*, per-group detection probability; *T*, survey time class (SM or MS); $w_i$, Akaike weight; ΔAICc, the difference between AICc of each model and AICc of the most parsimonious model; *λ*, mean abundance of blond titi monkey groups.

## 2.4 | Ethical statement

We comply with the Code of Best Practices for Field Primatology and this study is authorized by Chico Mendes Brazilian Institute for Biodiversity Conservation (SISBIO 52222-1). The research adhered to the American Society of Primatologists Principles for the Ethical Treatment of Non-Human Primates.

# 3 | RESULTS

We obtained 65 *C. barbarabrownae* group records from 157 surveys conducted in the 34 sites (Table 1). Forty-seven group records (72%) were obtained from sunrise to midmorning (5:05 a.m. to 9:59 a.m.; File S1). The maximum number of groups recorded in one single day was 14, and the maximum number of groups recorded at the same site in one day was 3.

The model including survey time as a predictor of detection and both forest area and distance to the nearest village as predictors of *C. barbarabrownae* group abundance was the best model (Table 2). However, models including only forest area or distance to the nearest village as predictors of abundance, and only survey time as a predictor of detection (with no predictor for abundance) showed small loss of information compared to the best model (ΔAICc < 4; Table 2). These four first-ranked models had a good fit for the data according to the $\chi^2$ statistic (values of observed $\chi^2$ were between the 2.5% and 97.5% range of simulated datasets from the model; Table 2). Accordingly, we used model averaging considering the four first-ranked models for estimates of detection, abundance, and relationships with predictors. For estimates based on each model, see Table 2.

Group detectability was influenced by survey time. Point counts conducted between 5:05 a.m. to 9:59 a.m. had a four times higher detection probability ($p = .48$; 95% confidence interval [CI], 0.27–0.70) than surveys between 10:00 a.m. to 5:50 p.m. ($p = .11$; 95% CI, 0.06–0.19). The number of groups increased as forest area increased in a site ($\beta = .46$; $SE = 0.25$; 95% CI, −0.03–0.95) and with increasing site distance from the nearest village ($\beta = .59$; $SE = 0.27$; 95% CI, 0.05–1.12; Figure 4). According to model averaging estimates, a given sampling site with 0.01 or 0.48 km$^2$ (the smallest and biggest home ranges of blond titi monkeys) would have one group of

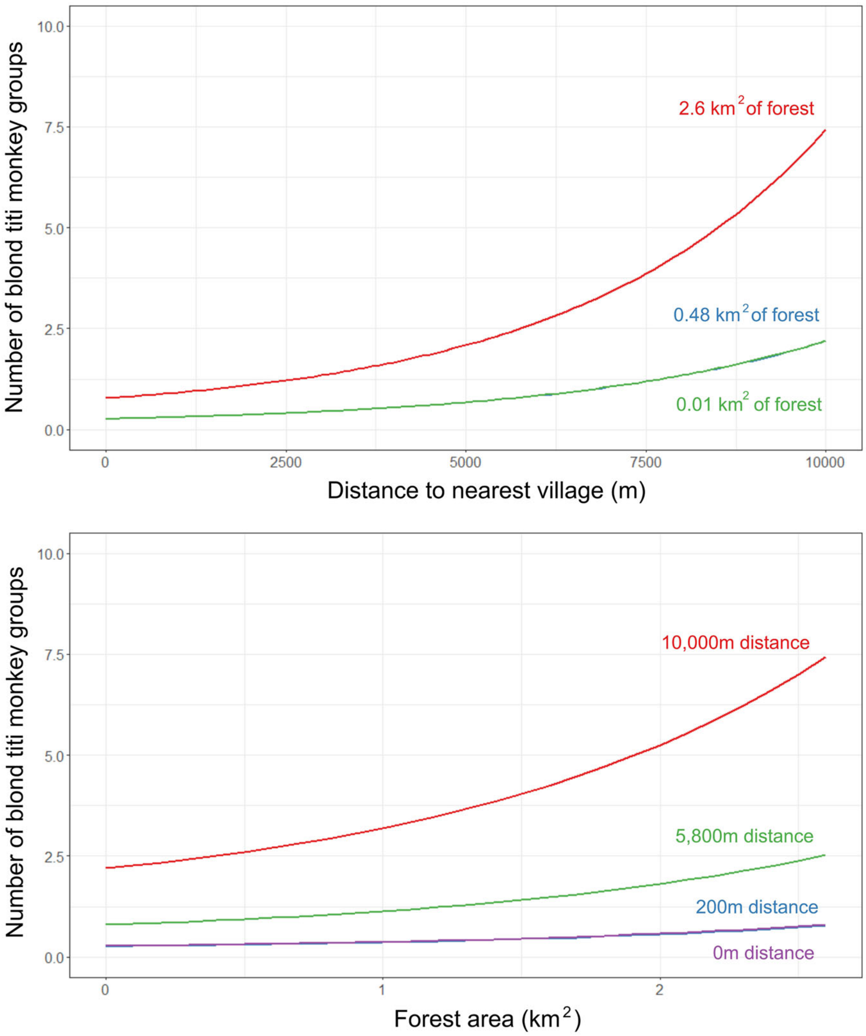


**FIGURE 4** The number of blond titi monkey groups predicted by model averaging as a function of distance to the nearest village (top) and forest area in a 2.6-km$^2$ sampling site (bottom). For distance to nearest village varying from 0 to 10,000 m, three fixed values of forest area: 0.01, 0.48 (the smallest and biggest home ranges of blond titi monkeys), and 2.6 km$^2$ (a sampling site totally covered by forest). For forest area varying from 0 to 2.6 km$^2$, four fixed values of distance to nearest village: 0, 200 (the distance for which one group was estimated in a site with 2.6 km$^2$ of the forest), 5,800 (the distance for which one group was estimated in a site with 0.01 or 0.48 km$^2$ of the forest), and 10,000 m

*C. barbarabrownae* only if it were at least 5,800 m from the nearest village (Figure 4). Conversely, a given sampling site totally covered by forest (2.6 km$^2$) would have one group of blond titi monkey if it were at least 200 m far from villages (Figure 4).

The mean number of *C. barbarabrownae* groups across the 34 sampling sites was 1.5 (mean 95% CI, 0.8–3.3), ranging from 0.4 (95% CI, 0.1–1.3) in the lowest abundance site to 2.9 (95% CI, 1.3–6.2) in the highest. The mean estimate across the 85 hexagons covering the study area was 1.4 groups (mean 95% CI, 0.6–3.2), ranging from 0.3 (95% CI, 0.09–1.2) to 3.7 (95% CI, 1.5–9.4). Applying the conservative rounding criterion produced an estimate of 91 (95% CI, 29–254) blond titi monkey groups in the entire study area (Figure 3; File S2). This indicates a density of 0.4 groups/km$^2$ in the whole area, or 0.8 groups/km$^2$ in dry forest habitat in the area. Considering the average group size of three adults, we estimate the local population size of 273 (95% CI, 87–762) adult individuals, resulting in a density of 1.2 individuals/km$^2$ in the entire study area or 2.3 individuals/km$^2$ in dry forest habitat.

## 4 | DISCUSSION

Our study estimated that blond titi monkey abundance is higher than previously thought. The description of the species in 1990 (Hershkovitz, 1990) and more recent population studies suggested that the species is rare and facing a high risk of extinction. Corsini and Moura (2014) observed only three groups in line transects (relative abundance of 0.19 groups/10 km walked), although the auditory records were higher ($n = 13$; 0.85 groups/10 km). Freitas et al. (2011) had only two group sightings in 133 km of line transects. The 273 adult individuals estimated to inhabit the 221-km$^2$ in our study area contrasts with a minimum population size of 260 adult individuals in 2,636 km$^2$, the total occurrence area of the species (Printes et al., 2011). Our local population estimate is greater than the population size threshold (250 adult individuals) used as one criterion to classify the species as critically endangered (Printes et al., 2018; Veiga et al., 2008), indicating an urgent need for more reliable information on population sizes of endangered primates. Playback point counts in conjunction with N-mixture models can be a useful method to sample and estimate the abundance of acoustically-responsive species, such as other primates and birds.

As expected, *C. barbarabrownae* abundance was related to dry forest area and distance to villages, confirming the importance of native forests for the species' distribution. Anthropic land covers in the Caatinga, such as villages, shrublands, *Eucalyptus* sp. plantations, and pasture are probably not suitable for the species. There is no evidence for the use of anthropic land covers for 70% of primate species, which is a reason for the current primate extinction crisis (Galán-Acedo et al., 2019). We also confirmed that blond titi monkey detectability was highest from sunrise to midmorning, indicating that playback counts should be conducted during the species' highest response period, or that sampling time must be considered as a predictor of detection in acoustic surveys.

Having a short survey period is important for meeting the population closure assumption when applying models to estimate the abundance of closed populations (e.g., N-mixture models; Royle, 2004). However, our study could be improved by having more sampling sites and occasions. Specifically, our estimates of the relationships between the number of groups and predictors could be more precise if we had more variation in forest area and distance to villages among sampling sites. A probabilistic sampling design, instead of an opportunistic one, could also improve precision in our estimates, and should be planned a priori (Smith et al., 2017). In addition, our detection probability estimates could be improved by including a predictor variable related to the difference in detection among sites. A candidate variable to be tested in future studies is a measure of sound propagation from the playback point to the site area, maybe using slope and land cover.

Although our findings indicate that *C. barbarabrownae* abundance is not as low as previously thought, the estimated density in our study area (2.3 individuals/km$^2$ in forest habitat) is lower than any estimate for other titi monkey species (from 4 to 28.7 individuals/km$^2$; Bicca-Marques & Heymann, 2013), suggesting a need for conservation management of blond titi monkeys in the Caatinga. Similar population assessments in other areas of the Caatinga are necessary to confirm other potential source areas for the species and to determine the total population size. Reliable assessments of population trends are also crucial for the evaluation of the conservation status of blond titi monkeys. On the basis of our results, we recommend the protection and increase of dry forest habitat in the Caatinga and promotion of conservation awareness in human settlements near known populations of *C. barbarabrownae* to maintain and enhance abundance. Anthropogenic areas represent 63% of the Caatinga biome (Silva & Barbosa, 2017) and 91% of remaining native vegetation fragments are smaller than 5 km$^2$ (Antongiovanni, Venticinque, & Fonseca, 2018). Actions to promote *C. barbarabrownae* conservation (ICMBio, 2018) will require a major shift from the current ways in which land is managed in the Caatinga (Tabarelli, Leal, Scarano, & Silva, 2017), bringing economic and cultural value to dry forests.

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### DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in Table 1 and in the Supporting Information Material of this article.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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