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ORIGINAL ARTICLE

Monitoring the annual vocal activity of two enigmatic nocturnal Neotropical birds: the Common Potoo (*Nyctibius griseus*) and the Great Potoo (*Nyctibius grandis*)

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Abstract

Potoos (*Nyctibius* spp.) are nocturnal Neotropical canopy-dwelling birds, making them one of the most enigmatic and least known avian families. The Common Potoo (*Nyctibius griseus*) and the Great Potoo (*Nyctibius grandis*) are the most widespread species, but little information on their life histories is available. We evaluated the utility of autonomous recording units, coupled with automated signal recognition software, to monitor the calling behavior of both species for the first time over a complete annual cycle at six different sites in the Brazilian Pantanal. Their diel activity was restricted to the night, with higher calling rates after midnight. The breeding season of the Common Potoo, according to seasonal changes in vocal activity, seems to occur between July and November, while the breeding period of the Great Potoo extended from July to December. The reproduction periods proposed for each potoo in this study correspond mainly with the dry season in the study area and are in agreement with the few historical nest site observations from Brazil. The maximum calling activity of both species occurred between 1 and 5 a.m. September was the month with the maximum vocal activity of the Common Potoo, while the Great Potoo was most vocally during October. The vocal activity of neither potoo was related to night temperature. The Great Potoo was more vocally active during nights with high moon illumination. Our results will be useful in future monitoring programs for these species. Acoustic monitoring has proven to be a helpful tool for monitoring the presence and calling seasonality of the Common Potoo and the Great Potoo, mainly due to their naturally low vocal activity rates. Acoustic monitoring should be evaluated and used to increase our knowledge about the ethology and ecology of this enigmatic avian family.

Keywords Autonomous recording unit · Calling activity · Climate · Kaleidoscope Pro · *Nyctibiidae* · Passive acoustic monitoring · Seasonality

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Zusammenfassung

Erfassung der jährlichen Gesangsaktivität zweier eigenartiger, nachtaktiver neotropischer Vogelarten: des Urutau-Tagschläfers (*Nyctibius griseus*) und des Riesentagschläfers (*Nyctibius griseus*)

Tagschläfer (*Nyctibius* spp.) sind nachtaktive neotropische Vögel, die in Baumkronen leben und zu den eigenartigsten und am wenigsten untersuchten Vogelarten gehören. Der Urutau-Tagschläfer (*Nyctibius griseus*) und der Riesentagschläfer (*Nyctibius grandis*) sind die am weitesten verbreiteten Arten, aber es liegt nur wenig Information über ihre Lebensart vor. Wir testeten den Nutzen autonomer, mit automatisierter Signalerkennungssoftware ausgestatteter Aufnahmegeräte, um zum ersten Mal über ein komplettes Jahr hinweg das Rufverhalten beider Arten an sechs unterschiedlichen Standorten im brasilianischen Pantanal aufzuzeichnen. Ihre Aktivitätszeit beschränkte sich auf die Nacht, wobei die Anzahl ihrer Rufe nach Mitternacht höher als davor war. Aufgrund der jahreszeitlichen Änderungen seiner Lautäußerungen nehmen wir an, dass die Brutzeit des Urutau-Tagschläfers zwischen Juli und November liegt, während die Brutzeit des Riesentagschläfers von Juli bis Dezember reicht. Die Fortpflanzungszeit beider von uns untersuchten Arten lag überwiegend in der Trockenzeit in unserem Untersuchungsgebiet, was den wenigen, alten Beobachtungen an Neststandorten in Brasilien entspricht. Die meisten Lautäußerungen gab es bei beiden Arten nachts zwischen 1 und 5 Uhr. Der Urutau-Tagschläfer zeigte die größte Ruf-Aktivität im September, wohingegen das Ruf-Maximum des Riesentagschläfers im Oktober lag. Bei beiden Arten gab es keinen Zusammenhang mit der nächtlichen Temperatur. Der Riesentagschläfer war in Nächten mit starkem Mondlicht Ruf-aktiver. Unsere Ergebnisse werden für zukünftige Überwachungsprogramme für diese Arten von Nutzen sein. Die akustische Überwachung hat sich als nützliches Werkzeug für die Überwachung der Anwesenheit und der jahreszeitlichen Ruf-Aktivität von Urutau-Tagschläfer und Riesentagschläfer erwiesen, was in erster Linie an ihrer ohnehin niedrigen Ruf-Aktivität liegt. Akustisches Monitoring sollte eingesetzt werden, um unser Wissen über das Verhalten und die Ökologie dieser eigenartigen Vogelfamilie zu erweitern.

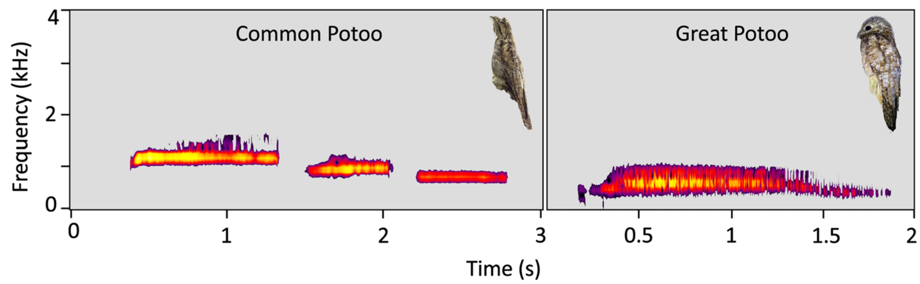
Introduction

Potoos (Nyctibiidae) comprises seven nocturnal species represented by a single genus (*Nyctibius*, but see Costa et al. 2018) restricted to the Neotropics (Cohn-Haft 1999). All members of this taxon are insectivorous and famous for their cryptic plumage and upright, motionless posture on trees during the day, causing them to resemble a branch (Cleere 2010). Due to their nocturnal canopy-dwelling habit and cryptic and secretive behavior, potoos comprise one of the most enigmatic avian families (Cleere 2010). Among the potoos, the most widespread are the Common Potoo (*Nyctibius griseus*) and the Great Potoo (*Nyctibius grandis*) (Cleere 2010). Both species inhabit rainforest areas as well as dry forests, cerrado savannas, and tall secondary growth forests (Cohn-Haft 1999). The Common Potoo is widely distributed in southern Central America and in the northern and central parts of South America, while the Great Potoo is distributed throughout Central and South America (Cleere 2010).

Our current knowledge about the natural history of the Common Potoo and the Great Potoo is limited and restricted to a few countries. For example, the breeding biology of the Common Potoo has been examined to some detail in Costa Rica (Skutch 1970) and Mexico (Álvarez del Toro 1971). However, there are only anecdotal or incidental notes about the ecology of the species in other countries (e.g., Tate 1994; Cestari et al. 2011; Sánchez-Martín and Yusti-Muñoz 2016). The lack of knowledge is even greater for the Great Potoo, whose life history is virtually unknown (but see Vanderwerf 1988; Navarro et al. 2011 and references therein). Nonetheless, potoo ecology may differ among areas according to differences in climatic seasons (Costa et al. 2010); therefore, there is a need to increase our understanding of their ecology outside the studied areas.

The presence of potoos "is known mainly through their strange calls" (Wetmore 1968). However, the frequency of the vocal activity of potoos can be erratic and even low during the breeding season compared with that of other nocturnal birds, such as owls and nightjars (Skutch 1970; Cleere 2010; Solano-Ugalde 2011). This unpredictable vocal activity may explain why some potoos have been unrecorded for several years (Skutch 1970; Cohn-Haft 1993; Ingels et al. 2008; Costa et al. 2010). The Common Potoo and the Great Potoo have distinctive calls. The main call of the Common Potoo is composed of a descending series of a few (3–6) melancholy notes, which start loud and gradually drop-in pitch in sliding steps as they decrease in volume ("Waaoo, woo-woo-wuuhh", Voudouris 2015; Fig. 1). The call of the Great Potoo is a strong and guttural "wahhhoooo" (Cleere 2010; Fig. 1). The particularity of the calls of both species suggests that the use of autonomous recording units, when coupled with automated signal recognition, might be a potential solution for obtaining new life history information on this enigmatic family (Obrist et al. 2010). Previous studies have demonstrated the utility of autonomous recording units for monitoring rare species (Sidie-Slettedahl et al. 2015; Pérez-Granados et al. 2018a; Schroeder and Mcrae 2020) as well as the nocturnal calling activity of tropical birds (Farnsworth and Russell 2007; Goyette et al. 2011; Shonfield and Bayne 2017; Pérez-Granados et al. 2020).

Fig. 1 Sonogram of a typical call, with three syllables, of the Common Potoo (left) and Great Potoo (right) recorded in the Pantanal Matogrossense (Brazil)



In this study, we describe and quantify the calling activity of sympatric Common and Great Potoos in the Brazilian Pantanal. We employed passive acoustic monitoring over a complete annual cycle at six different acoustic monitoring stations. Our objectives were to (1) evaluate the use of autonomous recording units to monitor the presence and calling activity of both species for the first time; (2) describe the patterns of diel and seasonal variation in calling activity of both species to gain insights into their ecology; (3) identify the hours and months with the highest calling activity; (4) evaluate whether the vocal activity of both potoos was associated with daily minimum air temperature (as a surrogate of night temperature) and percent of the moon illuminated; and (5) estimate the minimum number of sound recording days required to detect the presence of each species as a valuable reference for future studies in other localities.

Material and methods

Study area

The study area was located in the northeastern part of the Brazilian Pantanal, near the SESC Pantanal (Pantanal Matogrossense, Poconé municipality, Mato Grosso, Brazil; 16°30′ S, 56°25′ W; see Supplemental Online Resource 1). The Common Potoo and the Great Potoo are the only two species of potoos known to inhabit the Brazilian Pantanal (Tubelis and Tomas 2003, pers. obs). The area surveyed was close to the Cuiabá River (one of the main tributaries of the Paraguay River), and it is seasonally inundated from October to April due to flooding of the Paraguay River (Junk et al. 2006). The dominant vegetation in the study area is composed of a mosaic of different forest formations and savannas (Junk et al. 2006). More detailed information on the local avian and vegetation communities in the study area can be found in de Deus et al. (2020). The climate in the region is tropical and humid, with an average annual rainfall between 1000 and 1500 mm and a mean annual temperature of approximately 24 ℃. During the monitored annual cycle, the total annual rainfall in the study area was 1131 mm and the rainfall regime followed the typical seasonal pattern, with 1025 mm (90.6% of the total) accumulated during the wet season (October–April). The mean annual temperature during the studied year was 25.5 ℃.

Acoustic monitoring

Six acoustic monitoring stations separated between 573 and 2750 m were established in the study area (mean separation of 908.0 ± 168.7 m, mean ± SE, Supplemental Online Resource 1) as part of the INAU project "Sounds of the Pantanal—The Pantanal Automated Acoustic Biodiversity Monitoring" (https://cobra.ic.ufmt.br). The location of the acoustic monitoring stations were established to (1) cover the most representative vegetation formations of the Brazilian Pantanal (forest and savannas), (2) keeping a minimum distance of 500 among recorders, and (3) have private access to avoid human disturbance. Although the stations were not established for exclusively monitoring the Common and the Great Potoo the whole study area was a potential habitat for both species according to the main habitat types occupied for both potoos (Cohn-Haft 1999).

At each acoustic monitoring station, we deployed one Song Meter SM2 recorder (Wildlife Acoustics, https://www.wildlifeacoustics.com) at 1 m height attached to trees. The recorders operated daily from 8 June 2015 to 31 May 2016. The distance at which the recorders are able to record bird vocalizations differs among species according to their different frequencies (Yip et al. 2017). Likewise, the detection probability of bird vocalizations is much decreased when recording in closed (forested) areas than in open habitats (Yip et al. 2017) and should be also decreased for canopy-dwelling bird species that do not vocalize towards the recorder position (Pérez-Granados et al. 2019a). These findings together with the fact that we did not find overlapping calls among adjacent stations and that the diel and seasonal patterns of calling activity found between the two closest stations (stations B and C) were dissimilar, suggest that the risk of recording the same individual at two different stations might be low (Rempel et al. 2013, Pérez-Granados et al. 2019a) (see Supplemental Tables for hourly and monthly call production at each station). The recorders were programmed to record (in stereo and .wav format) the first 15 min of each hour in 24/7 mode with the following parameters: hourly time, GMT-4; sampling rate, 48 kHz; and resolution, 16 bits per sample. Recordings were stored on SD memory cards capable of storing ~ 250 h of recordings. The recorders were powered by four 1.5 V alkaline batteries (Duracell MN13000) (~ 160 h autonomy) and checked weekly to download data and change batteries. A total of 47,942 15-min recordings were collected (8044 in Station A, 7829 in Station B, 8075 in Station C, 7782 in Station D, 8090 in Station E, and 8122 in Station F).

Acoustic data analyses

The left channel of recordings was scanned with Kaleidoscope Pro 5.1.8. (Wildlife Acoustics, https://www.wildlifeacoustics.com). Kaleidoscope Pro is an automated signal recognition software able to scan recordings for candidate sounds, based on the following signal parameters: minimum and maximum frequency ranges (Hz), minimum and maximum times of detection (s), and a maximum inter-syllable gap (ms). To introduce accurate signal parameters, we used a dataset composed of 34 and 30 calls of the Common Potoo and the Great Potoo, respectively, recorded in the study area. These calls were measured from spectrograms using Raven Pro 1.5 (Bioacoustics Research Program 2014) with the following configuration: Hamming window function; 71% brightness; 79% contrast; 256 point DFT size; and 50% time grid overlap. We measured the dominant frequency (Hz) using the peak frequency measurement function; lower and higher frequencies (Hz) using the frequency 5% and frequency 95% functions and call duration (s). A summary table showing the mean (± SD) duration, minimum frequency, maximum frequency and dominant frequency of the call of each potoo in the study area can be found in Table 1.

The signal parameters input into Kaleidoscope were as follows: minimum and maximum frequencies (400 and 1400 Hz, respectively), minimum and maximum lengths of detection (0.8 and 6 s, respectively, to detect overlapping individuals), and maximum intersyllable gap (0.3 s). The maximum intersyllable gap is considered the maximum allowable gap between syllables; thus, syllables separated by less than 0.3 s were considered to be part of the same call. Kaleidoscope Pro requires one additional parameter for scanning the recordings: "Maximum distance from cluster center to include outputs". This parameter ranges from 0 to 2 and it has an impact on the number of signals detected. Larger values result in a large number of target signals but it will also increase the number of false positives (misclassified signals). We set the parameter "maximum distance from cluster center to include outputs" to 2 since we aimed to detect the maximum number of calls possible (see Pérez-Granados et al. 2020 for quantitative analyses of the number of bird calls detected and precision of a bird recognizer using variable values of the maximum distance from cluster center parameter). The recordings were scanned only one time, using the same settings to detect both species after performing a preliminary test that revealed that Kaleidoscope Pro was able to detect 96.7% (29 calls) and 88.2% (30 calls) of the Common Potoo and Great Potoo calls, respectively, annotated in the training dataset.

We used the cluster analysis function of Kaleidoscope. Kaleidoscope extracts the Discrete Cosine Transform coefficients (DCT) of the spectrum of the candidate sounds (those sounds that fit with the signal parameters introduced). A Hidden Markov Model is constructed from the vector of the DCT of each signal frame and the vectors are grouped using K-Means clustering. Therefore, candidate sounds detected by Kaleidoscope are automatically grouped into groups of similar sounds called "clusters". Clusters are formed by moving vocalizations to existing clusters if they are similar (i.e., if they are within the "maximum distance from cluster center"). Otherwise, a new cluster is created. Candidate sounds are also sorted within clusters by similitude. Thus, most of the signals within a definite cluster belong to the same vocalization of the species, and the first songs of each cluster are the most similar and representative of each group. We labeled each cluster identified by Kaleidoscope Pro as "Common Potoo", "Great Potoo" or "other sounds" according to whether or not a call of the desired species was detected within the first 50 events of each cluster. The events of the clusters labeled as "other sounds" were not checked and were excluded from posterior analyses. Finally, every event labeled "Common Potoo" or "Great Potoo" was visually and/or acoustically checked, always by the same observer (CPG) to separate false positives from true positives.

We estimated the precision of the recognizer, a typical index of recognizer performance, by dividing the number of true positives (correct classifications) by the total number of candidate sounds classified within the cluster "Common Potoo" and "Great Potoo" (Brauer et al. 2016;

Table 1 Mean ± SD (and range) of the acoustical parameters of Common Potoo and Great Potoo calls in the Pantanal Matogrossense (Brazil)

Species	Duration (s)	Minimum frequency (Hz)	Maximum frequency (Hz)	Dominant frequency (Hz)
Common Potoo	3.30 ± 0.51 (2.23–4.07)	538.6 ± 78.2 (382.1–731.8)	1295.7 ± 99.8 (1164.8–1518.2)	1036.3 ± 61.9 (937.5–1125)
Great Potoo	1.31 ± 0.34 (0.88–1.86)	290.3 ± 121.8 (145–471.3)	1028.4 ± 96.2 (906.3–1196.4)	679.9 ± 128.4 (468.8–845.8)

A total of 40 and 36 calls of the Common Potoo and the Great Potoo, respectively, from nine different recordings were measured. Recordings were collected using a Song Meter SM2 recorder (Wildlife Acoustics), and call measurements were made using Raven Pro 1.5

Knight et al. 2017). We also calculated the recall of the cluster classification made by Kaleidoscope for each species. The recall rate is an index that represents the proportion of target species vocalizations automatically detected and is a typical metric for assessing recognizer performance (Heinicke et al. 2015; Knight et al. 2017). We estimated the recall rate of the recognizer of each species by dividing the total number of true positives detected by Kaleidoscope by the total number of calls uttered by the Common or the Great Potoo during the recordings (Knight et al. 2017). The total number of calls of each potoo species on each recording was annotated always by the same experienced observer (CPG) after checking visually and acoustically the selected recordings. We reviewed a total of 168 different 15-min recordings looking for each species, divided in the three following categories: (A) 30 recordings with known presence of each species according to Kaleidoscope analyses (five recordings per station for the Great Potoo and seven or eight recordings per occupied station for the Common Potoo, 60 recordings in total); (B) 30 recordings randomly selected between those recorded during the period with significant maximum calling activity of each species (see results, five recordings per site for each species, 60 recordings in total); and (C) 48 nocturnal recordings randomly selected from our dataset (eight recordings, made between 6 p.m. and 5 a.m., per site). Recordings were reviewed blinded with respect to station identification, date of recording and whether or not the species were detected. Additionally, we estimated the false-negative rate of the recognizer. We estimated the false-negative rate for each species by dividing the total number of potoos calls misclassified by the recognizer by the total number of "other sounds" events reviewed. We reviewed a total of 20,000 sounds of the "other sounds" cluster randomly selected among those recordings made at night and between August and October and, therefore, with a high probability of detecting a misclassified call of the potoos. In the following link, we provide a compilation of ten snippets of calls of the Common Potoo and the Great Potoo as well as a 4-min recording length with several calls of the species made during the study period (https://cobra.ic.ufmt.br/?page_id=587).

Environmental variables

Weather data were collected from a meteorological station located at Station B. We collected the daily maximum, mean and minimum air temperature (℃) and daily rainfall (mm) throughout the study period. For each day we also collected the percentage of the moon illuminated from the US Naval Observatory (https://aa.usno.navy.mil/data/docs/MoonFraction.html).

Statistical analyses

To identify the hours with the highest calling activity for each potoo, we fitted an independent generalized linear model (GLM) for each species using the percentage of calls detected per hour in each month as the response variable and recording hour as a predictor (24 levels). In both species, we estimated the total number of calls detected at each hour of the day by summing the total number of calls detected at each hour at every station for statistical purposes. The number of months considered for the Common Potoo was reduced to seven since in the remaining 5 months, the species was not detected or detected only a few times (< 10 calls). An independent generalized linear mixed model (GLMM) was fitted for each potoo species to identify the months with significantly higher calling activity. In this case, we used the number of calls detected per monitoring day at each site as the response variable, month (12 categorical levels) as a fixed effect and station (four and six categorical levels for the Common Potoo and the Great Potoo, respectively) as a random effect to control for intersite variation. In both analyses (GLM and GLMM), when a fixed effect was found to be significant, Tukey's post hoc test was performed to test for differences between levels.

We fitted a logistic regression to assess the impact of daily minimum air temperature (used as a surrogate of night temperature) and percent of the moon illuminated on the probability of recording each species. We fitted an independent regression for each potoo using the daily vocal activity (active/inactive) of each species as the response variable; daily minimum air temperature or percent of the moon illuminated as predictors and station (four and six categorical levels for the Common Potoo and the Great Potoo, respectively) as a random effect. We focused that analyses to the month of September for the Common Potoo and to the month of October for the Great Potoo, the ones with significant calling activity for each species (see "Results"). We did not include daily rainfall on the assessment because the number of rainy days was low for statistical purposes (only 3 and 5 days with raining events > 3 mm in September and October, respectively). Finally, we estimated the number of monitoring days required to detect the presence of the Common Potoo and the Great Potoo during the months of September and October, respectively. The probability of recording species presence was estimated by fitting a logistic regression model with the detection of the species at each site on each date (yes/no) as the dependent variable, date as a predictor and station (four and six categorical levels for the Common Potoo and the Great Potoo, respectively) as a random effect. All statistical analyses were performed with R 3.6.2 (R Development Core Team 2019). We used the packages "lme4" (Bates et al. 2015) for GLMM construction, "lmerTest" (Kuznetsova et al. 2014) to calculate the *p* value (significance) of fixed effects and "multcomp" (Hothorn et al. 2008) for post hoc comparison tests. The level of significance was $p < 0.05$.

Results

The Kaleidoscope Pro output reported a total of 1,306,603 events that matched the signal parameters, which were classified into the following categories: "other sounds" included 1,292,173 events (98.90% of the total), "Common Potoo" included 3807 events (0.29% of the total), and "Great Potoo" included 10,622 events (0.81% of the total). The Common Potoo was detected at four of the six acoustic monitoring stations, with a variable number of calls per station between 74 and 109. The Great Potoo was detected at all monitoring stations, and the number of calls detected per station varied between 43 and 2095. A summary of the calling activity of the Common Potoo and the Great Potoo at each monitoring station over the annual cycle monitored can be found in Table 2.

The precision of the recognizer for the Common Potoo was 9.4% (357 calls in 3807 events) and 28.6% for the Great Potoo (3033 calls in 10,622 events detected). Recall rate for the Common Potoo was 85.2% (167 calls detected of the 196 calls annotated in the 168 recordings of the validation data set) and 73.6% for the Great Potoo (292 calls detected of the 397 annotated). The false-negative rate for the Common Potoo was 0.015% (3 calls detected among the 20,000 events reviewed) and 0.09% for the Great Potoo (9 calls detected among the 20,000 events reviewed). Although the events classified as "other sounds" were not fully checked, the analyses of the 20,000 events revealed that they were composed mainly of bird vocalizations of species that sang at the same frequency that the potoos. Most of these vocalizations were calls of common species in the study area, such as the Little Nightjar (*Setopagis parvula*) and the Undulated Tinamou (*Crypturellus undulatus*), but several cow (*Bos taurus*) calls were also found.

Diel activity pattern

Both potoos called only during the night and were vocally inactive between 6 a.m. and 5 p.m. (Fig. 2, and Online Resource 2 and Online Resource 3 for hourly call production at each station for the Common Potoo and the Great

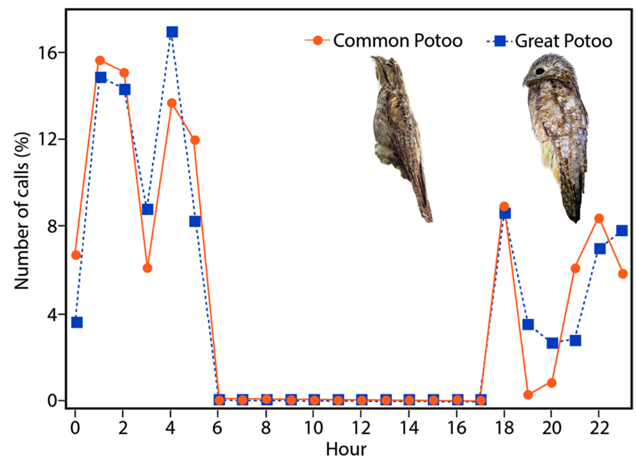


Fig. 2 Diel calling activity pattern of the Common Potoo (orange circles) and the Great Potoo (blue squares) in Pantanal Matogrossense (Brazil). Calling activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at six acoustic monitoring stations. The diel pattern of each species refers to the mean percentage of calls detected during each recording time per station. Hours are expressed in winter local time (UTC-4). The diel pattern of the Common Potoo is based on the average value among four acoustic monitoring stations since the species was not detected at two of the monitoring stations (colour figure online)

Table 2 Summary of vocal activity of the Common Potoo and the Great Potoo over an annual cycle in Pantanal Matogrossense (Brazil)

Species	Station	First song	Last song	Most active day	Most active hour	Most active month	Days detected
Common Potoo[a]	B	6 August	9 May	13 March	1 and 2 a.m.	November	29
	C	9 June	2 December	3 November	4 a.m.	November	28
	D	18 June	25 May	26 September	1 a.m.	September	7
	E	26 June	25 May	10 July	2 a.m.	September	22
Great Potoo	A	10 June	28 May	10 December	4 a.m.	October	54
	B	26 June	29 May	31 December	4 a.m.	October	50
	C	11 June	28 May	1 December	4 a.m.	October	112
	D	30 June	21 March	12 September	5 a.m.	September	11
	E	12 June	20 March	5 July	2 a.m.	August	33
	F	8 July	25 November	16 September	2 a.m.	August	18

Calling activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at six acoustic monitoring stations. Hours are expressed as UTC-4

[a]The species was not detected at stations A and F

Potoo, respectively). The diel patterns of the two species were similar (Fig. 2), with a first peak of calling activity just after dusk (at 6 p.m.), followed by a decrease in vocal activity in the following hours (Fig. 2). The vocal activity of both potoos during the night was variable but showed three peaks of vocal output at 10 p.m. and from 1 to 2 a.m. and at 4 a.m., which were followed by a decrease in vocal intensity at 3 a.m. and at 5 a.m., respectively (Fig. 2). According to the GLMs, the vocal activity of the Common Potoo and the Great Potoo varied between hours (Table 3). The Common Potoo showed significantly higher calling activity at 1 a.m. than at other hours, while the peak calling activity of the Great Potoo was reached at 4 a.m. (see Online Resource 4 for the results of Tukey's post hoc comparison for each species).

Seasonal activity pattern

The calling activity of the Common Potoo showed clear seasonality during the monitored annual cycle, with 87.4% of the total calls detected between July and November (Fig. 3). A small number of calls were detected during the remaining months, and no calls of the Common Potoo were detected during the months of January and February (Fig. 3) (see Online Resource 5 for monthly call production at each station). At one of the monitoring stations, the species was not detected later than 2 December (Table 2). The calling activity of the Common Potoo varied significantly between months (Table 4), and the vocal output in September was significantly higher than that in the other months (see Online Resource 6 for Tukey's post hoc comparison), with 29.1% of the total calls detected in September (Fig. 3). The calling activity of the Great Potoo showed less marked seasonality compared to the pattern described for the Common Potoo (Fig. 3) (see Online Resource 7 for monthly call production at each site). Although the Great Potoo was vocally active throughout the year, the species was detected for the last time in late November at one of the monitoring stations, and at two other stations, the species was not detected later than late March (Table 2). The peak calling activity of the Great Potoo occurred between July and December, a period during which 80.4% of the calls were detected. Similar to the pattern described for the Common Potoo, there was less calling activity in the Great Potoo from January to May (11.1% with respect to the total number of calls detected, Fig. 3). The vocal activity of the Great Potoo varied throughout the monitored annual cycle (Table 4), and October was the month with the greatest call production (18.4% with respect to the total, see Online Resource 6 for Tukey's post hoc comparison results).

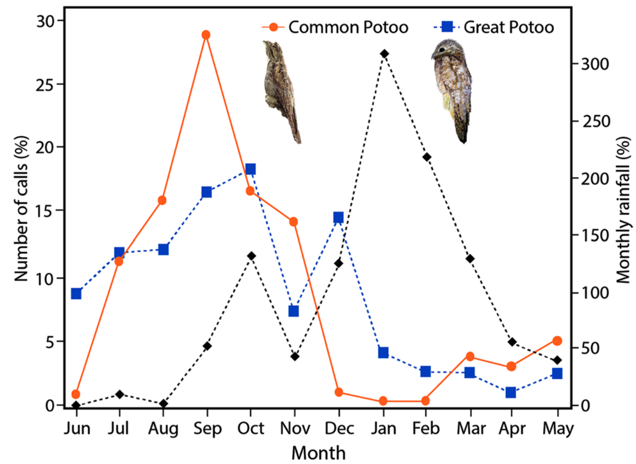


Fig. 3 Seasonal calling activity pattern of the Common Potoo (orange circles) and the Great Potoo (blue squares) in Pantanal Matogrossense (Brazil). Calling activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at six acoustic monitoring stations. The seasonal pattern is expressed as the mean percentage of calls detected at all stations per month (left *Y*-axis). The seasonal pattern of the Common Potoo is based on the average value among four acoustic monitoring stations since the species was not detected at two of the monitoring stations. The monthly accumulated rainfall (mm) (black squares), according to a weather station located in Station B is shown in the right *Y*-axis (colour figure online)

Environmental variables

According to the logistic regression, the vocal activity of the Common Potoo was not significantly related neither to daily minimum air temperature nor the percent of the moon illuminated (Table 5). The vocal activity of the Great Potoo was not related to daily minimum air temperature (Table 5). However, the Great Potoo vocal activity was significantly associated with the percent of the moon illuminated

Table 3 Summary table of type-III variance partitioning performed to test the effect of recording time on the calling activity of the Common Potoo and the Great Potoo in Pantanal Matogrossense (Brazil)

Species	*df*	Dev. Resid	*df* Resid	Dev	*F*	*p*
Common Potoo	23	5075.8	144	10,758	2.954	< 0.001
Great Potoo	23	8397.1	264	19,943	4.83	< 0.001

The effects of recording time on the calling activity of each species were assessed using independent generalized linear models. Calling activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at six acoustic monitoring stations

Table 4 Summary table of type-III variance partitioning performed to test the effect of the month on the calling activity of the Common Potoo and the Great Potoo in Pantanal Matogrossense (Brazil)

Species	*df*	Den. df	Sum Sq	Mean sq	*F*	*p*
Common Potoo	7	1391	91.5	8.32	3.04	< 0.001
Great Potoo	11	2104.1	1382.2	125.6	2.60	0.003

The effect of the month on the calling activity of each species was assessed using an independent generalized linear mixed model. Calling activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at six acoustic monitoring stations. Analyses for the Common Potoo are based on four acoustic monitoring stations since the species was not detected at two of the monitoring stations

Table 5 Summary results of a type-III variance partitioning of independent logistic regressions performed to assess the relationship between daily minimum air temperature and percent of the moon illuminated with the calling activity (active/inactive) of the Common Potoo and the Great Potoo in Pantanal Matogrossense (Brazil)

Species	Variable		Estimate	Std. error	*z* value	*p*
Common Potoo	Night temperature (°C)	(Intercept)	− 3.058	1.929	− 1.568	0.113
		Night temperature	0.067	0.101	0.66	0.507
	Moon illuminated (%)	(Intercept)	− 2.07	0.494	− 4.186	< 0.001
		Moon illuminated	0.005	0.007	0.666	0.505
Great Potoo	Night temperature (°C)	(Intercept)	− 3.201	2.388	− 1.343	0.179
		Night temperature	0.063	0.112	0.560	0.575
	Moon illuminated (%)	(Intercept)	− 3.418	0.825	− 4.143	< 0.001
		Moon illuminated	0.023	0.007	3.171	0.001

Station was included as a random effect. Calling activity was monitored using autonomous recording units during the month of September for the Common of Potoo and during October for the Great Potoo at six acoustic monitoring stations. Analyses for the Common Potoo are based on four acoustic monitoring stations since the species was not detected at two of the monitoring stations

(Table 5). The species was more vocally active on nights with a high percent of the moon illuminated (Fig. 4).

Monitoring protocol

The logistic regression fitted for the Common Potoo indicated that recording for the first 11 or 24 days of September is required to detect the presence of the species with a probability of detection higher than 50% and 90%, respectively (Fig. 5). The number of monitoring days required to detect the presence of the Great Potoo during the month of October with a detection probability higher than 50% and 90% was 9 and 28 days, respectively (Fig. 5).

Discussion

In this paper, we describe and analyze, for the first time, the diel and seasonal patterns of vocal activity of the Common Potoo and the Great Potoo over a complete annual cycle. Our current study fills a gap in knowledge of the ecology of these species in Brazil, a country for which very limited information is available (but see Corbo and Macarrão 2009; Mendonça et al. 2009; Cestari et al. 2011; Marini et al. 2012). The use of autonomous recording units and the Kaleidoscope Pro software enabled us to monitor the calling activity of both species at multiple locations throughout the full annual cycle and, therefore, accumulate enough data to

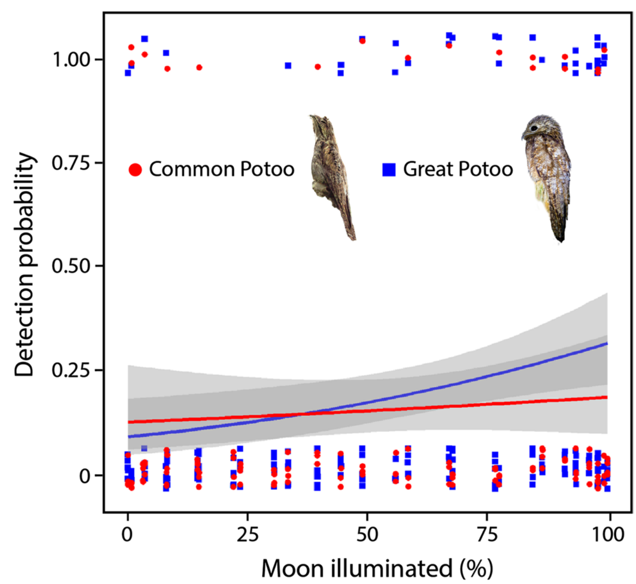


Fig. 4 Probability of detecting the presence of the Common Potoo (red circles) and the Great Potoo (blue squares) as a function of percent of the moon illuminated. Calling activity was monitored using autonomous recording units during the month of September for the Common Potoo and during October for the Great Potoo in Pantanal Matogrossense (Brazil). Calculations were based on logistic regressions (red line for the Common Potoo and blue lines for the Great Potoo), with the daily detection/no-detection of the species at four (Common Potoo) and six (Great Potoo) monitoring sites as the dependent variable and percent of the moon illuminated as the predictor variable. 95% confidence intervals are shown in grey (colour figure online)

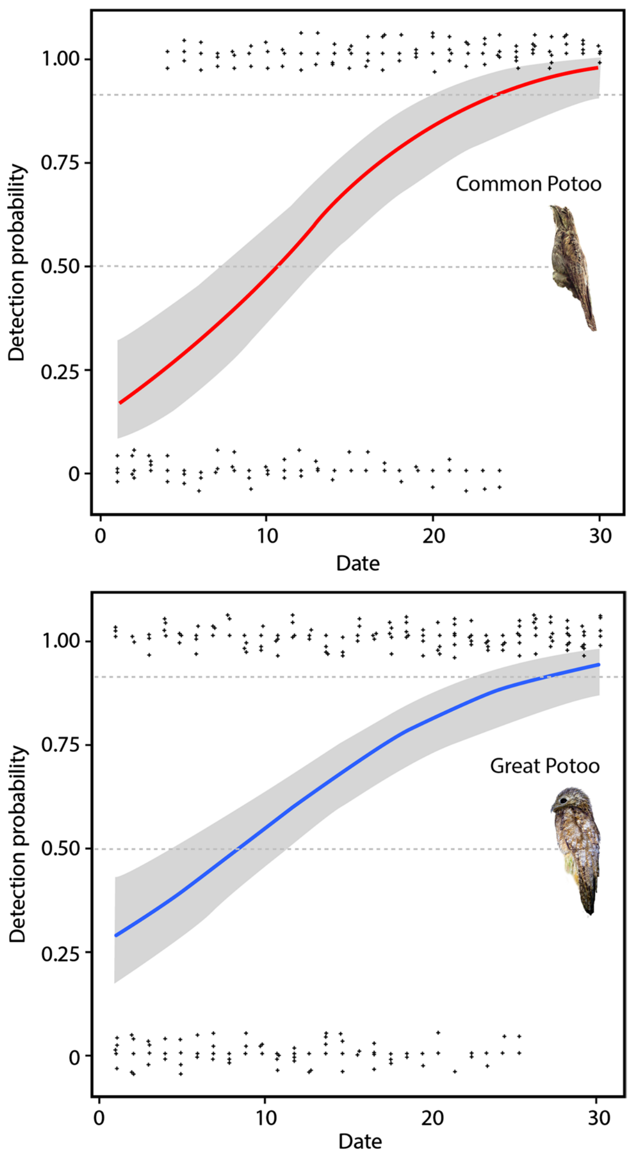


Fig. 5 Probability of detecting the presence of the Common Potoo (top) and the Great Potoo (bottom) in Pantanal Matogrossense (Brazil) during the month of September and October, respectively. Probability of detection is shown as a function of the number of monitoring days. Calculations were based on logistic regression (blue line), with the detection/no-detection of the species at four (Common Potoo) and six (Great Potoo) monitoring sites as the dependent variable and date as the predictor variable. 95% confidence intervals are shown in grey. Dashed lines show the 50 and 90% probability of detecting the species (colour figure online)

quantify changes in vocal activity throughout the year and at a daily scale. The effective use of autonomous recording units and the Kaleidoscope Pro to monitor both potoos is in agreement with the findings of previous studies demonstrating that such recorders and software can be a cost-effective tool for monitoring nocturnal birds (e.g. Pérez-Granados and Schuchmann 2020; Schroeder and Mcrae 2020).

The cluster classification carried out by Kaleidoscope Pro proved its efficacy to detect both species, since the recall rate obtained for both potoos ranged between 74% (Great Potoo) and 85% (Common Potoo), values that can be considered as high (e.g., recall rate of 1% for two marsh bird species, Bobay et al. 2018; mean value of 27.5% for four woodpecker species, Swiston and Mennill 2009, 40% for kiwis, Digby et al. 2013; mean value of 42.8% for four owls, Shonfield and Heemskerk 2018). The species were never detected by the human surveyor neither by Kaleidoscope on any of the recordings randomly selected ($n=48$) and each potoo was detected by humans and Kaleidoscope only on four of the 60 recordings randomly selected between those recorded during the period with significant maximum calling activity of each species. These results, together with the high recall rate estimated, support the assumption that the vocal activity of the Common Potoo and the Great Potoo is naturally low. Likewise, both species were detected by both methods in 100% of the recordings with known presence of each species according to Kaleidoscope analyses ($n=29$), validating the methodology employed for detecting the species presence. We found a low false-negative rate for both species (< 1%), despite that we only reviewed "other sounds" recorded during nights of the maximum vocal activity of the species, and, therefore, with a higher probability of detecting misclassified signals. This assessment shows that very few calls were misclassified by the cluster analyses function and suggests that most of the calls not detected by the recognizer were likely calls uttered from long distances and thus with a weak pattern to be detected by Kaleidoscope Pro. Our assessment also showed that most of the misclassified calls of the Great Potoo were originally grouped into clusters composed mainly of cow calls, which are similar in structure to the Great Potoo call. On contrary, the call structure of the Common Potoo is very particular (see Fig. 1) and, therefore, might be easier for Kaleidoscope to group the Common Potoo vocalizations into the specific cluster for the species. The precision of the recognizers can be considered low for both monitored potoos (range 9–29%) but they have no influence on our results since every event was verified and false positives were removed. Nonetheless, a very low precision can preclude the use of automated signal recognition software for detecting species' presence at large spatial and temporal scale, due to a large amount of time needed to remove false positives. However, the total number of sounds reviewed in our dataset was less than 15,000, which can be considered low if considering the high recall rate obtained and the large dataset analysed (c. 12,000 recording hours). The low percentage of sounds correctly classified as Common Potoo or as Great Potoo by Kaleidoscope Pro might be partly related to the signal parameters included on the software and to methods employed (e.g., large value used of the parameter "Maximum distance from cluster center to include outputs", see Pérez-Granados et al. 2020). Error rate of the cluster classification might have been significantly reduced using specific parameters for each species and scanning the recordings once for each species as well as by creating an advanced recognizer after labelling the events.

The diel pattern of calling activity of the Common Potoo and the Great Potoo revealed that these species call only during the nocturnal period, with a higher call rate after midnight. This pattern is in agreement with the typical nocturnal behavior of the family (Cleere 2010). Strictly nocturnal calling activity was found using the same monitoring technique in two other Neotropical caprimulgids, namely, the Little Nightjar and the Common Pauraque (*Nyctidromus albicollis*) (Pérez-Granados and Schuchmann 2020). More surprising are the small numbers of calls detected and vocally active days of both species during the study period despite the large amount of effort employed. The Common Potoo was detected on a mean number of 21.5 days per year and station, while the Great Potoo was detected on 46.3 days per year and station. In contrast, using the same dataset and the same automated signal recognition software, we were able to detect the Undulated Tinamou on 345 days per year and station (Pérez-Granados et al. 2020), while the Little Nightjar and the Common Pauraque were detected on 202 and 215.5 days per year and station, respectively (Pérez-Granados and Schuchmann 2020). This difference highlights that several cases in which the Common Potoo and Great Potoo have been unrecorded at some sites might be due to their low vocal activity (Skutch 1970; Cleere 2010).

The breeding season of the Common Potoo in the Brazilian Pantanal, according to seasonal changes in vocal activity, seems to occur between July and November. This period matches the dates of active nesting found for the species in other Brazilian regions (August–December, Mendonça et al. 2009; Corbo and Macarrão 2010; Cestari et al. 2011; Marini et al. 2012). The estimated breeding season in the Brazilian Pantanal corresponds mainly to the drier part of the year in the study area and agrees with the nesting ecology found during the dry season in Costa Rica (Skutch 1970). However, in southern Mexico (Álvarez del Toro 1971) and Venezuela (Tate 1994), the species breeds during the wet season, and in Colombia, Sánchez-Martín and Yusti-Muñoz (2016) found active nests of the species almost throughout the year (February, April, May and November). These results suggest that the breeding season of the Common Potoo may differ greatly among areas or that this species may not show any seasonal pattern (Cohn-Haft 1999). According to our results, the breeding season of the Great Potoo in the Brazilian Pantanal appears to take place between July and December. The breeding season proposed for the study area is fully in agreement with the period proposed for the species at other Brazilian sites (July–December, Sick 1951; Cleere 2010) and similar to those declared for Bolivia (July–August, Cleere 2010) and Venezuela (mid-June to mid-August, Vanderwerf 1988). However, current knowledge of the breeding biology of the Great Potoo is based on a very limited number of nests and, therefore, further research on the reproduction of the species is needed.

The Common Potoo and the Great Potoo are expected to be widespread species, but several authors have stated that their presence can be easily overlooked because of their cryptic coloration, low vocal activity, and nocturnal and canopy-dwelling habits (e.g., Skutch 1970; Vanderwerf 1988). For example, Skutch (1970) detected the presence of the Common Potoo in Costa Rica by sight (rather than hearing) nearly 24 years after he began to study the birds in the Valley of El General. This is in agreement with our results, which highlight the need to record (15 min per hour in 24/7 mode) for almost the entire month with maximum calling activity to detect the species' presence. This amount of recording is high compared to estimates from previous studies on nocturnally singing birds. For example, Pérez-Granados et al. (2018b) found that recording 1 h before dawn during two consecutive days was long enough to detect the presence of Dupont's Lark (*Chersophilus duponti*) in 100% of cases, even when the lark was present at very low density.

We found a positive and significant relationship between the percent of the moon illuminated and the vocal activity of the Great Potoo, which is in agreement with a large number of previous studies that found a positive impact of the moon on the vocal activity of different caprimulgids (e.g., Mills 1986; Perrins and Crick 1996; Reino et al. 2015). However, we did not find evidence that moonlight had an effect on the vocal activity of the Common Potoo that suggests that the response of the potoos to moonlight might be species-specific, as has been found also in different caprimulgids (Cadbury 1981; Debus 1997; Reino et al. 2015). However, we cannot rule out that the lack of relationship between the moonlight and the vocal activity of the Common Potoo might be related to the low number of days that the species was detected. The vocal activity of neither potoo was related to night temperature, which is in agreement with previous studies on caprimulgids that did not find any relationship between air temperature and vocal activity (Cadbury 1981). Night temperature during the study period was high and constant (mean values of 18.5 ℃ in September and 20.5 ℃ in October and coefficients of variation of 14.4% and 9.6% for September and October, respectively) which may have reduced the possibility of finding any significant relationship.

We hope that our results should prove useful for improving the efficiency of future surveys aimed at monitoring both species (using traditional or novel techniques), which will be especially important if both potoos continue to decline (BirdLife International 2016a, b). The Common Potoo and the Great Potoo should be monitored during the period elapsed between 1 a.m. and 5 a.m. when their calling activity is maximal. The probability of detecting the Great Potoo would be maximized when surveying the species under nights with a high percent of the moon illuminated. According to seasonal variations in calling activity, we suggest that the Common Potoo should be monitored during the month of September, while future surveys aiming to detect Great Potoo should be performed during October. Nonetheless, we are aware that the best monitoring periods for each species may differ among areas according to differences in climatic seasons (Costa et al. 2010) and among years according to seasonality (Pérez-Granados et al. 2019b).

The use of autonomous recording units, coupled with automated signal recognition software, has proven useful for monitoring the Common Potoo and the Great Potoo, a pair of birds that are difficult to monitor using traditional field surveys due to their infrequent vocal activity. We hope that this study will encourage researchers to develop specific recognizers and employ acoustic monitoring to improve our knowledge about the natural history of the other five species of potoos, for which the amount of available information is even smaller than that for the Common Potoo and the Great Potoo. This technique is very likely to lead to the discovery of previously unnoticed populations and redefine the current known distribution range for some of these species. The employment of specific recording analyses (e.g., individual recognition of calling birds, Ehnes and Foote 2015) or different monitoring protocols would open the door to further discoveries, including adequate information about the activity patterns and spatial movements of these species or estimates of their population densities (Blumstein et al. 2011; Marques et al. 2013).

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Availability of data and material The datasets analysed during the current study are not publicly available since they are being used for different scientific purposes, but are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Our study complies with current Brazilian laws and wildlife was not disturbed.

Consent to participate All researchers involved in the study are co-authors and consent voluntarily to be part of the present manuscript.

Consent for publication All authors agree with the publication of the manuscript in the selected journal.

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