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Automated signal recognition as a useful tool for monitoring little-studied species: The case of the Band-tailed Nighthawk

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ABSTRACT

Passive acoustic monitoring, when coupled with automated signal recognition software, is a useful technique for monitoring vocally active taxa. In this study, we evaluated the utility of automated signal recognition to gain insights into the ecology of little-studied species. For this purpose, we selected an avian family, Caprimulgidae (nightjars), composed of cryptic and nocturnal species, and focused the study on a Neotropical wetland, the Brazilian Pantanal. We reviewed the number of publications, observations, and recordings available for each nightjar inhabiting the Brazilian Pantanal and the Band-tailed Nighthawk (*Nyctiprogne leucopyga*) was identified as the species with the least information available. We employed automated signal recognition software to study the vocal behavior of this species over a complete annual cycle in the Pantanal. Previous knowledge about the ecology of this species is based on general descriptions and anecdotal observations. Our findings corroborate that the Nighthawk is a resident species of the Brazilian Pantanal, and according to seasonal changes in vocal activity, the breeding season extends from July to October. The breeding period starts at the end of the dry season (July–August), and the nesting period may occur at the beginning of the wet season and following the first rains, which is a period of maximum insect food availability. The vocal activity of the Nighthawk was restricted to the nocturnal period and was maximum at dusk. That preference for dusk is in disagreement with the pattern described for the other four nightjars in the study area, which highlights the importance of performing species-specific studies and avoiding drawing any conclusions about the activity pattern of a species based on the genus or family to which it belongs. Automated signal recognition software was able to detect over three quarters of the songs annotated by a human on a subset of sound recordings, therefore proving its utility for monitoring the Band-tailed Nighthawk.

1. Introduction

Global diversity has declined in recent decades and can be considered the sixth major extinction event (Maxwell et al., 2016; Pimm and Raven, 2000). The biodiversity crisis is enhanced in tropical forests, where deforestation is causing extinctions at unprecedented rates (Asfora and Pontes, 2009; Brooks et al., 1999), including extinctions of undescribed species (“dark extinction”) and species with few scientific records (Boehm and Cronk, 2021). In this context, there is a growing need for cost-effective methods to perform ecological monitoring at large spatial and temporal scales of biodiversity distribution and ecosystem health (Henry et al., 2008). Technological advances over recent decades have provided new and noninvasive techniques for wildlife monitoring, such as environmental DNA analyses, unmanned aerial vehicles and camera trapping (Saccò et al., 2022; Sardà-Palomera et al., 2017; Sebastián-González et al., 2019). Among the developments in noninvasive techniques, the use of passive acoustic monitoring has exponentially increased in recent years (Sugai et al., 2019).

Passive acoustic monitoring (PAM) requires the placement of unattended and programmable autonomous recording units (ARUs) in the

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field, followed by recording interpretation. Collected recordings can be processed visually or with the help of automated recognition software (Gupta et al., 2021; Stowell et al., 2019). PAM is a suitable alternative method to traditional surveys for monitoring wildlife across many research areas and taxa, including in terrestrial and aquatic environments (see reviews in Sugai et al., 2019, Desjonquères et al., 2020). Among the main advantages of using ARUs is the ability to monitor nocturnal and cryptic species in ecosystems difficult to reach for ecologists, such as tropical forests (e.g., Lambert and McDonald, 2014; Pérez-Granados and Schuchmann, 2020a).

Wildlife vocal activity has an important function in territorial defense and mate attraction (Catchpole and Slater, 2008; Wells and Schwartz, 2007). Therefore, the study of seasonal changes in wildlife vocal activity may be useful to provide insight into the ecology of vocally active taxa, for which the use of ARUs that can continuously monitor large remote areas, is highly valuable. For example, prior research employed ARUs to assess seasonal changes in calling activity and describe the breeding phenology of two recently described tropical frogs (*Philoria richmondensis* and *Elachistocleis matogrosso*, Willacy et al., 2015, Pérez-Granados et al., 2019). Similarly, passive acoustics was a reliable and efficient method to track the migration and seasonal occurrences of the Harbour porpoise (*Phocoena phocoena)* in the German Baltic Sea over two years (Gallus et al., 2012). Birds are the group of terrestrial animals most often monitored using ARUs (Sugai et al., 2019), including the study of year-round variation of vocal activity of tropical species (e.g., Pérez-Granados and Schuchmann, 2020a, 2020b; Szymański et al., 2021). Nonetheless, the use of PAM to provide ecological information about little-studied species should be further exploited. The collected information may be useful to improve our knowledge about species distributions, to propose effective sampling periods and to achieve diversity conservation.

In this study, we aimed to assess the effectiveness of PAM, when coupled with automated signal recognition software, to gain insights into the ecology of species with very limited information available. More specifically, we aimed to (1) develop an index that is easy and fast to compute and transposable to other regions and taxa, to identify species for which we have a clear gap of knowledge. We also aimed to (2) evaluate the use of automated signal recognition software as a feasible technique for monitoring cryptic and nocturnal bird species over a complete annual cycle at multiple sites. Such evaluation may be useful for future monitoring programs aiming to use automated signal recognition software. We have focused our study on a bird species living in tropical forests due to the high extinction risk of tropical birds (Brooks et al., 1999), but the lessons learned in this study might be useful for taxa living under different environmental conditions.

2. Materials and methods

2.1. *Criteria for identifying species with limited ecological information*

To identify the Brazilian nightjar with the least information available we created a combined index based on the following criteria: (i) number of scientific articles published about the species, (ii) number of observations uploaded to a citizen science platform, and (iii) number of recordings uploaded to a public online database of sounds. The latest version of the checklist of birds of Brazil includes 27 nightjars (Pacheco et al., 2021), although we restricted the search to those species inhabiting the Brazilian Pantanal (15 species, see Table 1), where the study was carried out (see study area section). The selection of species inhabiting the Brazilian Pantanal was based on whether there was at least one sighting uploaded to eBird on this area (http://www.ebird.org). eBird is a large-scale citizen science program focused on birds that enables interested ornithologists and citizen scientists to submit checklists of birds they have identified, which can be used for research purposes (e.g., Dansereau et al., 2022; Lin et al., 2022), and as of May 2021 over one billion of observations had been recorded in eBird.

Table 1
Number of scientific articles published on Google Scholar, number of observations uploaded to eBird and number of recordings stored in Xeno-canto for each nightjar inhabiting the Brazilian Pantanal. The data was extracted on 3 July 2022. The number between brackets refers to the rank of the species for each considered variable, while the mean rank shows the averaged value of each individual rank.

English name	Scientific name	Scholar Google	eBird	Xeno-canto	Mean rank
Rufous Nightjar	*Antrostomus rufus*	1 (2)	3132 (5)	107 (11)	6.0
Lesser Nighthawk	*Chordeiles acutipennis*	12 (13)	66,883 (13)	90 (9)	11.7
Common Nighthawk	*Chordeiles minor*	79 (15)	434,890 (15)	144 (13)	14.3
Ladder-tailed Nightjar	*Hydropsalis climacocerca*	2 (5)	3941 (7)	30 (2)	4.7
Band-winged Nightjar	*Hydropsalis longirostris*	4 (9)	8211 (11)	124 (12)	10.7
Spot-tailed Nightjar	*Hydropsalis maculicaudus*	2 (5)	1764 (1)	68 (7)	4.3
Little Nightjar	*Hydropsalis parvula*	1 (2)	4192 (8)	82 (8)	6.0
Scissor-tailed Nightjar	*Hydropsalis torquata*	2 (5)	5652 (9)	35 (3)	5.7
Short-tailed Nighthawk	*Lurocalis semitorquatus*	4 (9)	8482 (12)	147 (14)	11.7
Least Nighthawk	*Nannochordeiles pusillus*	4 (9)	1784 (2)	57 (6)	5.7
Blackish Nightjar	*Nyctidromus nigrescens*	9 (12)	3348 (6)	39 (5)	7.7
Common Pauraque	*Nyctidromus albicollis*	19 (14)	109,445 (14)	465 (15)	14.3
Ocellated Poorwill	*Nyctiphrynus ocellatus*	2 (5)	2607 (3)	97 (10)	6.0
Band-tailed Nighthawk	*Nyctiprogne leucopyga*	0 (1)	2652 (4)	39 (4)	3.0
Nacunda Nighthawk	*Podager nacunda*	1 (2)	6137 (10)	20 (1)	4.3

For each species we performed two literature searches, using its English and scientific names, to identify the number of scientific publications published about each considered nightjar. The search was carried out in Google Scholar spanning all years and considering only those studies where the species name appeared on the title of a study written in English, Portuguese or Spanish. When the same study was found in both searches, it was considered a single case study. The species were ranked in ascendant order according to the number of publications published, and therefore, the species with the lowest number of publications was ranked as first. In those cases where two different species had the same number of publications (or observations and recordings, see below), they were ranked equally. We considered that ranking as an index of the amount of scientific knowledge about the species. We also extracted the total number of observations of the species uploaded to eBird and the total number of recordings of each species stored in Xeno-canto (http://www.xeno-canto.org). Xeno-canto is a public, citizen-based, birdsong repository. It is a collaborative project dedicated to sharing (freely downloadable) bird sounds from all over the world, hosting over 714,000 recordings of 10,300 bird species. The platform has allowed the development of machine-learning algorithms able to automatically identify 3000 bird species by their sound (Wood et al., 2022) owing to the large number of labeled recordings uploaded by skilled ornithologists. We considered the eBird index as a proxy of bird rarefaction, where a lower number of observations could be related to a more restricted distribution of the species, while a lower number of recordings in Xeno-canto may indicate a species with a more limited vocal activity and for which it might be more difficult to collect ecological information (due to the nocturnal habits of the analyzed family). Likewise, both indices could be also considered as a surrogate of the amount of information available that could be used in future studies (e.g., eBird for species distribution modeling and Xeno-canto for creating an algorithm). The searches on Google Scholar, eBird and Xeno-canto were carried out on 3 July 2022. The total number of scientific articles in Google Scholar, observations uploaded to eBird and recordings stored in Xeno-canto for each species considered can be found in Table 1. The combined index was obtained by averaging the rank position of every species on the three considered categories, which identified the Band-tailed Nighthawk (*Nyctiprogne leucopyga*, Nighthawk hereinafter) as the nightjar with the least information available among those inhabiting the Brazilian Pantanal (Table 1).

2.2. Study species

The Band-tailed Nighthawk is a small and dark nightjar that occurs in northern Venezuela and eastern Colombia and east of French Guiana and south of Paraguay (Yoon, 2020). It usually occupies forests and savannas near water, although it is confined to the lowlands. The Nighthawk is crepuscular and nocturnal, and usually forages for flying insects in continuous flight (Ridgely and Greenfield, 2001). The species sings from a perch, not in flight (Yoon, 2020). The song is frog-like, and can be described as a distinctive leisurely *kowit… kowit….kowit* repeated steadily, which might be overlooked (Yoon, 2020, Fig. 1 and listen Supplementary Audio S1). The species is widespread and, at least locally, common although its population trend is believed to be decreasing (BirdLife International, 2016). In addition to the Nighthawk having a very large geographic range it remains a very poorly known species (BirdLife International, 2016, see also Table 1). Among the most pressing research priorities identified by the IUCN, there is the very little information on the reproductive biology, territoriality, and dispersal of the species (BirdLife International, 2016). For example, in Brazil we are only aware of one Nighthawk egg collected in northern Brazil in September (Snethlage 1935 in Yoon, 2020) with no more information available. Moreover, there is no information regarding the incubation, parental care, or nestling development of the species (Cleere and Nurney, 1998; Yoon, 2020).

2.3. Study area

The study area was located in the Brazilian Pantanal and comprised three monitoring stations around the SESC Pantanal resort (Mato Grosso, Brazil; 16°30′S, 56°25′W, Supplemental Fig. S1). The surveyed area is within the floodplain of the Cuiabá River and it is seasonally inundated during the wet season (October–April, Junk et al., 2006). The dominant vegetation was composed by a mosaic of savannas and forest formations (see detailed description in de Deus et al., 2020). The climate is humid and tropical, with average annual rainfall around 1000–1500 mm and a mean annual temperature about 24 °C (Junk et al., 2006).

2.4. Acoustic monitoring

A minimum distance of 800 m was considered to occur among the three acoustic monitoring stations to reduce the risk of recording the same individual from two adjacent sites (range 800–2800 m, Supplementary Fig. S1). That risk should be considered very low since the species sings from a perch, not in flight (Yoon, 2020).

One Song Meter SM2 recorder was left at each station, which operated from 8 June 2015 to 31 May 2016. The Song Meters recorded in stereo and .wav format and were programmed to operate the first 15 min of each hour, using a sampling rate of 48 kHZ and a bit sample of 16. Every week we checked the recorders to download data (stored in SD memory cards with ~250 h of storing capacity) and change the four 1.5 V alkaline batteries (~160 h of autonomy).

2.5. Acoustic data analyses and recognizer performance

Acoustic data analyses were carried out using Kaleidoscope Pro 5.4.7, which is an automated signal recognition software able to analyze large acoustic datasets. Kaleidoscope extracts sounds of interest based on the following five parameters: minimum and maximum signal length (s), minimum and maximum frequency range (Hz), and maximum intersyllable gap (ms). The maximum intersyllable gap represents the maximum distance between sounds to be considered part of the same vocalization. To identify representative parameters of the song of the Nighthawk we characterized 67 songs using all recordings uploaded in Xeno-canto and recorded in the State of Mato Grosso (eight recordings, see Supplemental Table S1). Song parameters were characterized from spectrograms using Raven Pro 1.5 (Bioacoustics Research Program, 2014). The signal parameters introduced in Kaleidoscope were: 900 and 1500 Hz (minimum and maximum frequency, respectively); 4 and 30 s (minimum and maximum length, respectively); and a maximum intersyllable gap of 4 s. In this step Kaleidoscope automatically extracted all sounds that satisfied the signal parameters introduced and saved the output.

We used the cluster analysis function of Kaleidoscope to: (i) group the candidate sounds in clusters, which are composed of groups of similar sounds, and to (ii) rank the candidate sounds by similarity within clusters (for a detailed description of the process, which is done automatically by Kaleidoscope see Pérez-Granados and Schuchmann, 2020a). In summary, the created clusters are composed by vocalizations of the same species and the first candidate sounds of the clusters are the best examples of that cluster. Kaleidoscope output can be filter using a confidence threshold that ranges from 0 to 2, and we set the value to 2 since we aimed to minimize overlooking Nighthawk vocalizations, although it may suppose an increase in the number of nontarget signals introduced (see Pérez-Granados et al., 2020).

All clusters were visually and acoustically checked and renamed as

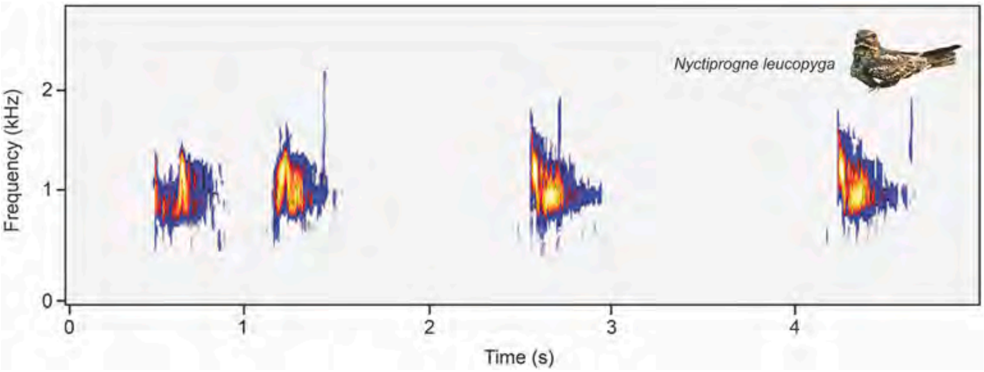

Fig. 1. Spectrogram of a typical song of the Band-tailed Nighthawk recorded in the Brazilian Pantanal (municipality of Poconé) during the study period with a Song Meter SM2 recorder.

"*Nighthawk*" or "*other sounds*" according to whether there was a Nighthawk vocalization within the first 50 sounds of the cluster (see validation in Pérez-Granados and Schuchmann, 2020a). Detections within the cluster "*Nighthawk*" were checked to separate mislabeled signals from true positives, while the cluster "*other sounds*" was excluded from posterior analyses.

Performance of the cluster analysis function of Kaleidoscope (recognizer hereafter) was evaluated by estimating its precision and recall rate, the two metrics most commonly employed for assessing bird recognizer performance (Knight et al., 2017). Precision was estimated by dividing the number of true positives (Nighthawk vocalizations) by the total number of candidate sounds within the cluster "*Nighthawk*" (Pérez-Granados and Schuchmann, 2020a). The recall rate was obtained by dividing the total number of true positives detected by Kaleidoscope by the total number of Nighthawk vocalization on the validation dataset. The validation dataset was composed of 210 15-min recordings, on which an experienced observer annotated the number of Nighthawk songs on each recording. The validation dataset was composed of: (i) 120 recordings (40 per station) with confirmed presence of the species according to Kaleidoscope, and (ii) 90 randomly selected recordings (10 recordings per station and month) recorded from July to September and at 18:00 or 05:00, when the vocal activity of the species was high (see results). The validation dataset was blindly reviewed, with no prior information of date of recording, station name or whether the Nighthawk was automatically detected by Kaleidoscope.

2.6. *Statistical analyses*

A Generalized Linear Model (GLM), with quasibinomial error structure, was fitted to assess whether singing activity of the Nighthawk varied over the day. The percentage of songs detected per recording hour was used as response variable, while recording hour, month and site were included as factor. The two latter variables were introduced to control for variations owing to site or vocal seasonality. To avoid biases the analyses were run considering only the period with high vocal activity (from June to September) and the hours (from 5 p.m. to 5 a.m.) when the species was vocally active. An independent GLM, with Gaussian error structure, was run to assess whether the singing activity of the Nighthawk varied over the monitored annual cycle and to identify the month with highest singing activity. In that case we used the number of songs detected per day (log transformed) as the response variable while recording month and site were introduced as factors. We did not include in the analyses those months with <100 vocalizations (from December to March, see results). We performed Tukey's post-hoc tests to identify differences among levels of the factor recording hour and recording month. Statistical analyses were run with R 3.6.2 (R Development Core Team, 2019). The package "multcomp" (Hothorn et al., 2008) was used for Tukey's post-hoc tests.

3. Results

The cluster "*Nighthawk*" was composed of 37,986 candidate sounds, of which a total of 7827 sounds were identified as Nighthawk sounds, and therefore the recognizer precision was 20.6%. A total of 543,810 sounds were classified in the cluster "*other sounds*". The recall rate of the recognizer was 76.8%, with a total of 857 Nighthawk vocalizations detected by Kaleidoscope from the 1115 detections within the validation dataset). See Table 2 for a summary of the vocal activity of the Nighthawk at each station.

3.1. *Diel activity pattern*

The singing activity of the Nighthawk varied among recording hours (Table 3) and was concentrated during the crepuscular period, with most of the songs detected after sunset (43.3% of total songs detected at 6 p.m., Fig. 2) and with a second, but smaller, peak just before sunrise (11.3% of total songs detected at 5 a.m., Fig. 2). The species showed low, but relatively constant, singing activity throughout the night (Fig. 2 and see Supplementary Table S2 for hourly production at each station). According to the post-hoc test, the singing activity of the Nighthawk was significantly higher at 6 p.m. (see Supplemental Fig. S2).

Table 2
Summary of vocal activity of the Band-tailed Nighthawk over an annual cycle. Vocal activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at three acoustic monitoring stations. Hours are expressed as UTC (−4).

Station	First Song	Last Song	Most Active Day	Most Active Hour	Most Active Month	Days Detected
A	9 June	27 May	30 August	6 p.m.	August	169
B	9 June	31 May	20 August	6 p.m.	August	181
C	8 June	31 May	2 July	6 p.m.	August	226

Table 3
Summary table of type-III variance partitioning performed to test the effects of recording time and month on the singing activity of the Band-tailed Nighthawk. The effects of recording time and month on the singing activity of the species were assessed using independent generalized linear models. Vocal activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at three acoustic monitoring stations.

	Variable	df	Dev. Resid.	df Resid.	Dev.	F	P
Recording time	*Hour*	12	21.37	143	4.19	55.79	<0.001
	—Station	2	0	141	4.19	0.001	1
	—Month	3	0	138	4.19	0.001	1
Month	*Month*	7	583.9	703	766.3	89.45	<0.001
	—Station	2	112.6	701	653.8	60.36	<0.001

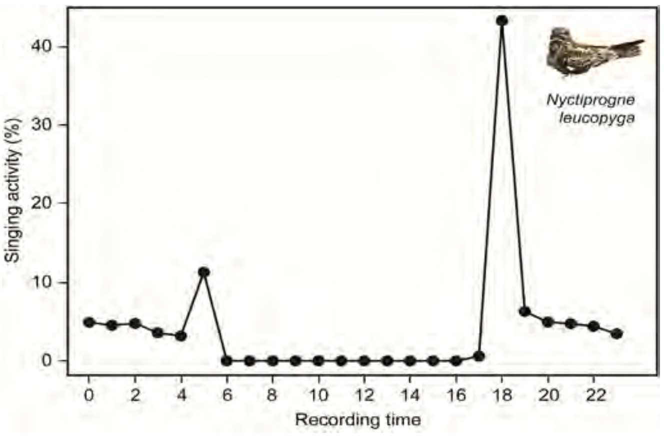

Fig. 2. Diel singing activity pattern of the Band-tailed Nighthawk. Singing activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at three acoustic monitoring stations. The diel pattern refers to the averaged percentage of songs detected during each recording time at all monitored sites. Hours are expressed in winter local time (UTC -4).

3.2. *Seasonal activity pattern*

The Nighthawk was detected monthly at two of the three monitored stations, while at Station A, it was detected only in ten of the 12 monitored months (see Supplementary Table S3 for monthly production at each station). Nonetheless, the species showed a definite seasonal pattern (Table 3), with 86.9% of the songs recorded from June to

September (Fig. 3). Maximal singing activity occurred between July and August, a period during which 60.2% of the total songs were detected, with August being identified as the month with significantly higher singing activity according to Tukey's post-hoc test (Supplementary Fig. S3).

4. Discussion

Here we report the results of a year-long study of the vocal behavior of the Nighthawk at three monitoring stations. Passive acoustic monitoring, coupled with automated signal recognition, allowed us to fill a gap in knowledge of the ecology of the Nighthawk for which very limited information is available by unravelling ecological patterns that otherwise might be difficult or impossible to assess using traditional field surveys (Willacy et al., 2015). For example, our acoustic analyses proved that Nighthawk is a resident species in the Pantanal Matogrossense. In regards to most aspects of the ecology of the species, there is little information about the migratory habits of the Nighthawk, and therefore our results can only be compared with anecdotal observations and general descriptions. Cleere and Nurney (1998) stated that movements of the species are poorly understood and that some populations were possibly sedentary, while others were migratory. In contrast to our results, prior research in the study area described the species as migrant, only occurring in the area from July to November (Pinho, 2005). This conflicting finding may be partly related to the use of passive acoustic monitoring in our study, which enabled us to monitor the species' presence almost continuously over a year and to detect its presence even when the singing activity was very low. In contrast, prior research used traditional field surveys and could have overlooked the species during the period of minimum singing activity (Pinho, 2005), which occurs from December onward (Fig. 3). Nonetheless, we cannot discard the possibility that the species may behave as partial migrants, leaving some areas of the Pantanal Matogrossense during the flooding season. Indeed, in previous studies of three resident nightjars in that area, all three species were detected throughout the year at some stations, while at close-distance stations (<2 km) the species were only detected during the breeding period (Pérez-Granados and Schuchmann, 2020a, 2020b), which suggests the existence of local movements of nightjars according to site-specific characteristics. These findings highlight the ability of passive acoustic monitoring to improve our knowledge about the migratory habits of bird species (e.g., Bota et al., 2020) and the importance of placing sound recorders at several sites and evaluating the recordings over the long term to provide an accurate description of the migratory and vocal behavior of the target species.

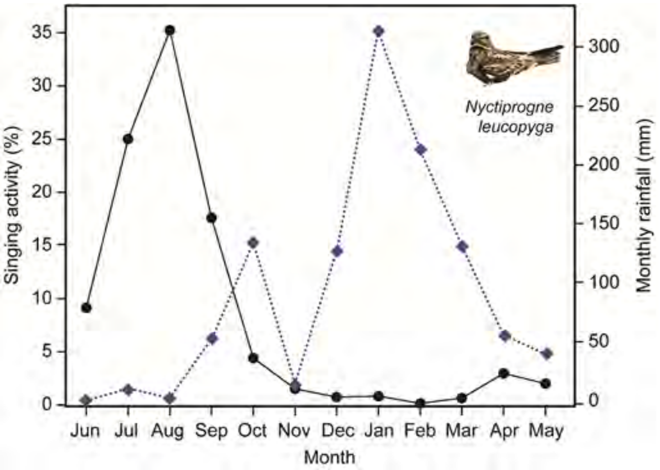

Fig. 3. Seasonal singing activity pattern of the Band-tailed Nighthawk. The seasonal pattern is expressed as the averaged percentage of songs detected per month at all monitored sites. The monthly accumulated rainfall (mm) (blue squares), according to a weather station in the study area is shown on the right Y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The breeding ecology of the Nighthawk has been poorly studied with no information regarding incubation, parental care, or nestling development, and only anecdotal descriptions about its breeding period in a few countries, excluding Brazil (Cleere and Nurney, 1998; Yoon, 2020). Seasonal changes in the singing activity of the species suggest that the breeding period of the Nighthawk in the Pantanal Matogrossense occurs between July and September. The abundance of tropical insects usually increases following the first rainfall events after the dry season (Jetz et al., 2003; Wolda, 1978), which during the monitored year took place between 7 and 9 September during the monitored year (32 mm in total, with only a small rainfall event of 2.2 mm during August). Prior research in Guinea of the Standard-winged Nightjar (*Macrodipteryx longipenni*) found that courtship displays of the species began approximately six weeks before the first short rains and gave signs of the forthcoming wet season, since it coincided with a period during which aerial insect biomass was maximum for nesting development (Jetz et al., 2003). According to that phenomenon we hypothesized that the mating period of the Nighthawk in the study area may occur between July and August, the period with maximum singing activity, which may relate to courtship displays and territory defense, while the incubation and nesting development period may occur during September and October, when there is a relaxation of singing activity and maximum food availability. The suggested incubation period agrees with the only known, to our knowledge, record of an egg collected in September in northern Brazil (Snethlage 1935, in Yoon, 2020). We are aware that the proposed periods are based on seasonal changes in singing activity and that the described patterns may slightly vary among years according to rainfall regime. Further research should aim to collect observational data about the reproduction of the species to provide an accurate description of the breeding ecology of Nighthawk.

The diel pattern of the vocal activity of the Nighthawk was restricted to the crepuscular and nocturnal periods in agreement with prior research with four other Caprimulgidae in the study area (Pérez-Granados and Schuchmann, 2020a, 2020b). The nocturnal singing activity of the species is not surprising, although we expected to find a limited number of songs during the diurnal period, since several nighthawks are partially diurnal and even the Band-tailed Nighthawk has been proposed to be rarely diurnal (Cleere and Nurney, 1998). Nonetheless, we cannot discard the possibility that the species may forage at certain periods of the day while not vocalizing. The Nighthawk showed a clear peak of singing activity just after dusk, which is in agreement with a previous description of the preference of the species for foraging at dusk (Acheson and Davis, 2001; Bates et al., 1989; Shany et al., 2007). Nonetheless, the diel pattern found differs from that previously described for four other Caprimulgidae species in the study area. The Little Nightjar (*Setopagis parvula*) and the Great Potoo (*Nyctibius grandis*) showed peak of singing activity a few hours before sunrise (4–5 a.m.), while the vocal activity of the Common Potoo (*Nyctibius griseus*) peaked at midnight (1 a.m., Pérez-Granados and Schuchmann, 2020a, 2020b). The only species with a maximum of vocal activity around dusk (6 p.m.) was the Common Pauraque (*Nyctidromus albicollis*), although that peak was as high as that occurring before sunrise (5 a.m.), showing a clear preference for both crepuscular periods. Therefore, the Nighthawk is the only species with a preference for vocalizing just at dusk. Our results highlight the importance of performing species-specific studies to characterize the vocal patterns of target species and to avoid drawing any conclusions about the activity pattern of a species based on the genus or family to which it belongs to.

The recall rate (76.8%) obtained in our study is in agreement with previous studies that used the same automated recognition software for monitoring four nightjars in the study area (range 71–85%, Pérez-Granados and Schuchmann, 2020a, Pérez-Granados et al., 2022) but much higher than the values obtained for the other two Caprimulgidae species when using a different software (e.g., 31% for the Eastern Whip-poor-will, *Antrostomus vociferous*, Knight et al., 2022). Recognizer performance greatly varies with the automated signal recognition software employed. For example, Knight et al. (2017) using a nightjar, the Common Nighthawk (*Chordeiles minor*), as the model species evaluated the performance of five automated recognition software programs and proved that the recall rate may vary from 75% ("MonitoR" package, Katz et al., 2016) to 20% (Song Scope) among programs. These findings highlight the utility of passive acoustic monitoring for detecting nightjars and the ability of Kaleidoscope Pro to detect nightjar vocalizations from sound recordings. The precision of our algorithm (20.6%) is among the lowest of values previously published for Brazilian nightjars using Kaleidoscope Pro (range 9–29% for two potoo species, Pérez-Granados and Schuchmann, 2020a), but much lower than that estimated for two other Brazilian nightjars (range 71–77%, Pérez-Granados and Schuchmann, 2020b). Similarly, Knight et al. (2017, 2022) estimated the precision for the Eastern Whip-poor-will and the Common Nighthawk to be approximately 45% and 70%, respectively, when using Song Scope and Kaleidoscope Pro, respectively. The low precision of our recognizer has had no impact on our results, since every candidate sound of the cluster "*Nighthawk*" was verified. Nonetheless, low precision may preclude the utility of passive acoustic monitoring in future studies carried out at large temporal or spatial scales owing to the amount of time needed for manual review. In addition, we estimated that reviewing all candidate sounds within the cluster "Nighthawk" took us approximately 72 working hours, which represents approximately 1.2% of the total time recorded (c. 6000 recording hours). Kaleidoscope Pro ability to detect the Band-tailed Nighthawk in a different area may be slightly different owing to geographical song variations since the signal parameters introduced in our study were extracted from recordings collected at different sites of the state of Mato Grosso and based on a reduced sample size (eight recordings). The creation of more advanced classifiers using machine learning or convolutional neural networks might be useful in future studies aiming to reduce the number of sounds misclassified (LeBien et al., 2020).

Passive acoustic monitoring has proven its ability for wildlife monitoring and to provide new information on the behavioral ecology of several taxa (Dufourq et al., 2021; Sugai et al., 2019; Szymański et al., 2021). In this context, a novelty of the present study is that we used PAM, coupled with automated signal recognition software, to fill a clear gap in our knowledge of the ecology of a bird species. The developed index can be easily adapted to other areas and to identify and monitor other vocally-active taxa, not only birds, with reduced information available. Further research may evaluate the need to remove or add categories to the proposed index, such as species vulnerability (Benayas and de la Montaña, 2003), according to the main objective of the study. Finally, our results might also contribute to improving future monitoring programs aimed at monitoring the Nighthawk by identifying the concrete periods (July–September and at dusk) during which further research should be conducted to improve the likelihood of detection.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Cristian Perez-Granados reports financial support was provided by CAPES. Karl-L. Schuchmann reports financial support was provided by Instituto Nacional de Ciência e Tecnologia em Áreas Úmidas. Karl-L. Schuchmann reports financial support was provided by Brehm Funds for International Bird Conservation.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2022.101861.

References

Acheson, A., Davis, S., 2001. Birding in Parque Nacional noel Kempff Mercado, Bolivia. Cotinga 16, 91–96.

Asfora, P.H., Pontes, A.R.M., 2009. The small mammals of the highly impacted North-Eastern Atlantic Forest of Brazil, Pernambuco endemism center. Biota. Neotrop. 9, 31–35.

Bates, J.M., Garvin, M.C., Schmitt, D.C., Schmitt, C.G., 1989. Notes on bird distribution in northeastern Dpto. Santa Cruz, Bolivia, with 15 species new to Bolivia. Bull. Br. Ornithol. Club 109, 236–245.

Benayas, J.M.R., de la Montaña, E., 2003. Identifying areas of high-value vertebrate diversity for strengthening conservation. Biol. Conserv. 114 (3), 357–370.

Bioacoustics Research Program, 2014. Raven pro: interactive sound analysis software. In: Version 1.5. Computer Software. The Cornell Lab of Ornithology, Ithaca, NY. Available from. http://www.birds.cornell.edu/raven.

BirdLife International, 2016. Nyctiprogne leucopyga. IUCN Red List Threatened Species 2016 e.T22689720A93245073.

Boehm, M.M., Cronk, Q.C., 2021. Dark extinction: the problem of unknown historical extinctions. Biol. Lett. 17 (3), 20210007.

Bota, G., Traba, J., Sardà-Palomera, F., Giralt, D., Pérez-Granados, C., 2020. Acoustic monitoring of diurnally migrating European bee-eaters agrees with data derived from citizen science. Ardea 108 (2), 139–149.

Brooks, T.M., Pimm, S.L., Oyugi, J.O., 1999. Time lag between deforestation and bird extinction in tropical forest fragments. Conserv. Biol. 13 (5), 1140–1150.

Catchpole, C.K., Slater, P.J.B., 2008. Bird Song, Biological Themes and Variation, 2nd ed. Cambridge University Press, Cambridge, U.K.

Cleere, N., Nurney, D., 1998. Nightjars: A Guide to the Nightjars and Related Nightbirds. Pica Press, Robertsbridge.

Dansereau, G., Legendre, P., Poisot, T., 2022. Evaluating ecological uniqueness over broad spatial extents using species distribution modelling. Oikos 2022 (5), e09063.

de Deus, F.F., Schuchmann, K.-L., Arieira, J., de Oliveira Tissiani, A.S., Marques, M.I., 2020. Avian beta diversity in a neotropical wetland: the effects of flooding and vegetation structure. Wetlands 40 (5), 1513–1527.

Desjonquères, C., Gifford, T., Linke, S., 2020. Passive acoustic monitoring as a potential tool to survey animal and ecosystem processes in freshwater environments. Freshw. Biol. 65 (1), 7–19.

Dufourq, E., Durbach, I., Hansford, J.P., Hoepfner, A., Ma, H., Bryant, J.V., Turvey, S.T., 2021. Automated detection of Hainan gibbon calls for passive acoustic monitoring. Remote Sens. Ecol. Conserv. 7 (3), 475–487.

Gallus, A., Dähne, M., Verfuß, U.K., Bräger, S., Adler, S., Siebert, U., Benke, H., 2012. Use of static passive acoustic monitoring to assess the status of the 'critically Endangered'Baltic harbour porpoise in German waters. Endanger. Species Res. 18 (3), 265–278.

Gupta, G., Kshirsagar, M., Zhong, M., Gholami, S., Ferres, J.L., 2021. Comparing recurrent convolutional neural networks for large scale bird species classification. Sci. Rep. 11 (1), 1–12.

Henry, P.Y., Lengyel, S., Nowicki, P., Julliard, R., Clobert, J., Celik, T., Gruber, B., Schmeller, D.S., Babij, V., Henle, K., 2008. Integrating ongoing biodiversity monitoring: potential benefits and methods. Biodiv. Conserv. 17, 3357–3382.

Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous inference in general parametric models. Biometrical. J. J. Math. Method Biosci. 50 (3), 346–363.

Jetz, W., Steffen, J., Linsenmair, K.E., 2003. Effects of light and prey availability on nocturnal, lunar and seasonal activity of tropical nightjars. Oikos. 103 (3), 627–639.

Junk, W.J., Da Cunha, C.N., Wantzen, K.M., Petermann, P., Strüssmann, C., Marques, M. I., Adis, J., 2006. Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil. Aquat. Sci. 68 (3), 278–309.

Katz, J., Hafner, S.D., Donovan, T., 2016. Tools for automated acoustic monitoring within the R package monitoR. Bioacoustics 25 (2), 197–210.

Knight, E.C., Hannah, K., Foley, G., Scott, C., Brigham, R., Bayne, E.M., 2017. Recommendations for acoustic recognizer performance assessment with application to five common automated signal recognition programs. Avian Cons. Ecol. 12 (2), 14.

Knight, E., Hannah, K., DeMoor, J., 2022. In the still of the night: revisiting eastern whip-poor-will surveys with passive acoustic monitoring. Avian Conserv. Ecol. 17 (1).

Lambert, K.T., McDonald, P.G., 2014. A low-cost, yet simple and highly repeatable system for acoustically surveying cryptic species. Aust. Ecol. 39 (7), 779–785.

LeBien, J., Zhong, M., Campos-Cerqueira, M., Velev, J.P., Dodhia, R., Ferres, J.L., Aide, T. M., 2020. A pipeline for identification of bird and frog species in tropical soundscape recordings using a convolutional neural network. Ecol. Informat. 59, 101113.

Lin, H.Y., Binley, A.D., Schuster, R., Rodewald, A.D., Buxton, R., Bennett, J.R., 2022. Using community science data to help identify threatened species occurrences outside of known ranges. Biol. Conserv. 268, 109523.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M., 2016. Biodiversity: the ravages of guns, nets and bulldozers. Nature 536, 143–145.

Pacheco, J.F., Silveira, L.F., Aleixo, A., Agne, C.E., Bencke, G.A., Bravo, G.A., de Q Piacentini, V., 2021. Annotated checklist of the birds of Brazil by the Brazilian ornithological records committee—second edition. Ornithol. Res. 29 (2), 94–105.

Pérez-Granados, C., Schuchmann, K.-L., 2020a. Monitoring the annual vocal activity of two enigmatic nocturnal Neotropical birds: the common Potoo (Nyctibius griseus) and the great Potoo (Nyctibius grandis). J. Ornithol. 161 (4), 1129–1141.

Pérez-Granados, C., Schuchmann, K.-L., 2020b. Illuminating the nightlife of two Neotropical nightjars: vocal behavior over a year and monitoring recommendations. Ethol. Ecol. Evol. 32 (5), 466–480.

Pérez-Granados, C., Schuchmann, K.-L., Ganchev, T., Strüssmann, C., Dorado-Rodrigues, T.F., Tissiani, A.S.D.O., Marques, M.I., 2019. Elucidating the diel and seasonal calling behaviour of Elachistocleis matogrosso (Anura: Microhylidae). J. Nat. Hist. 53 (43–44), 2699–2710.

Pérez-Granados, C., Schuchmann, K.-L., Marques, M.I., 2020. Vocal behaviour of the undulated Tinamou (*Crypturellus undulatus*) over an annual cycle in the Brazilian Pantanal: new ecological information. Biotropica. 52, 165–171.

Pérez-Granados, C., Schuchmann, K.-L., Marques, M.I., 2022. Addicted to the moon: vocal output and diel pattern of vocal activity in two Neotropical nightjars is related to moon phase. Ethol. Ecol. Evol. 34 (1), 66–81.

Pimm, S.L., Raven, P., 2000. Extinction by numbers. Nature 403 (6772), 843–845.

Pinho, J.B., 2005. Riqueza de espécies, padrões de migração e biologia reprodutiva de aves em quatro ambientes florestais do Pantanal de Poconé, MT. (Tese de Doutorado). Universidade Federal de Minas Gerais, Belo Horizonte.

R Development Core Team, 2019. A Language and Environment for Statistical Computing R Foundation for Statistical Computing, Vienna.

Ridgely, R.S., Greenfield, P.J., 2001. The Birds of Ecuador: Volume 1: Status, Distribution, and Taxonomy. Comstock Publishing Associates, Ithaca, NY.

Saccò, M., Guzik, M.T., van der Heyde, M., Nevill, P., Cooper, S.J., Austin, A.D., White, N. E., 2022. eDNA in subterranean ecosystems: applications, technical aspects, and future prospects. Sci. Total Environ. 153223.

Sardà-Palomera, F., Bota, G., Padilla, N., Brotons, L., Sardà, F., 2017. Unmanned aircraft systems to unravel spatial and temporal factors affecting dynamics of colony formation and nesting success in birds. J. Avian Biol. 48 (9), 1273–1280.

Sebastián-González, E., Barbosa, J.M., Pérez-García, J.M., Morales-Reyes, Z., Botella, F., Olea, P.P., Sánchez-Zapata, J.A., 2019. Scavenging in the Anthropocene: human impact drives vertebrate scavenger species richness at a global scale. Glob. Chang. Biol. 25 (9), 3005–3017.

Shany, N., Alván, J.D., Alonso, J.Á., 2007. Finding white-sand forest specialists in Allpahuayo-Mishana reserve, Peru. Neotropical. Birding 2, 60–68.

Stowell, D., Wood, M.D., Pamuła, H., Stylianou, Y., Glotin, H., 2019. Automatic acoustic detection of birds through deep learning: the first bird audio detection challenge. Methods Ecol. Evol. 10 (3), 368–380.

Sugai, L.S.M., Silva, T.S.F., Ribeiro Jr., J.W., Llusia, D., 2019. Terrestrial passive acoustic monitoring: review and perspectives. BioScience 69 (1), 15–25.

Szymański, P., Olszowiak, K., Wheeldon, A., Budka, M., Osiejuk, T.S., 2021. Passive acoustic monitoring gives new insight into year-round duetting behaviour of a tropical songbird. Ecol. Indic. 122, 107271.

Wells, K.D., Schwartz, J.J., 2007. The Behavioral Ecology of Anuran Communication. In Hearing and Sound Communication in Amphibians. Springer, New York, NY, pp. 44–86.

Willacy, R.J., Mahony, M., Newell, D.A., 2015. If a frog calls in the forest: bioacoustic monitoring reveals the breeding phenology of the endangered Richmond range mountain frog (Philoria richmondensis). Aust. Ecol. 40 (6), 625–633.

Wolda, H., 1978. Fluctuations in abundance of tropical insects. Am. Nat. 112 (988), 1017–1045.

Wood, C.M., Kahl, S., Rahaman, A., Klinck, H., 2022. The machine learning–powered BirdNET app reduces barriers to global bird research by enabling citizen science participation. PLoS Biol. 20 (6), e3001670.

Yoon, H.S., 2020. Band-tailed nighthawk (*Nyctiprogne leucopyga*), version 1.0. In: Schulenberg, T.S. (Ed.), Birds of the World. Cornell Lab of Ornithology, Ithaca, NY, USA. https://doi.org/10.2173/bow.batnig1.01.