Diel and seasonal variation of Striped Cuckoo (*Tapera naevia*) vocalizations revealed using automated signal recognition

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Studying seasonal changes in the vocal activity of birds may shed light on the function of avian vocalizations and the phenology of life history events. Our current knowledge regarding the seasonality of the vocal behaviour of tropical birds in general, and avian brood parasites in particular, is very limited. Here, we employed passive acoustic monitoring with automated signal recognition to monitor the vocal behaviour of the Striped Cuckoo *Tapera naevia* over a complete annual cycle in the Brazilian Pantanal. We evaluated whether the pattern of vocal activity differed between the two main vocalizations of the species (*sem-fim* and *wee-series* songs) and whether vocal activity varied with time of day and season. The diel pattern of vocal activity for both vocalization types showed a bimodal pattern, with the first peak of vocal activity in the few hours after sunrise and the second peak before sunset, in agreement with prior studies in other cuckoos. The *sem-fim* song was also produced during the night, while the *wee-series* song was produced only during the day. Both vocalization types showed clear seasonality and were produced between mid-June and mid-February. Seasonal changes in vocal activity suggest that the Striped Cuckoo breeds during the dry season and leaves the study area during the flooding period. The seasonal pattern of the *wee-series* song showed strong seasonality, with 90% of these calls detected in September and October, whereas the *sem-fim* song showed weaker seasonality, with 80% of the calls detected during the July–October period. Our study indicates that automated signal recognition might be a reliable tool for monitoring cuckoos. Further research could evaluate whether the different seasonal patterns of the *sem-fim* and *wee-series* songs of the Striped Cuckoo are related to different functions.

Keywords: autonomous recording unit, Cuculidae, Kaleidoscope Pro, Neotropical, passive acoustic monitoring.

Birds vocalize to communicate with conspecifics, mainly to attract mates or establish territory, but avian vocalizations can also have other purposes, such as maintaining group contact or signalling about food, danger or avian diversity (Marler 2004, Catchpole & Slater 2008, Morelli *et al.* 2017, Gil & Llusia 2020). Previous studies in several bird species have demonstrated that seasonal changes in vocal activity can be associated with changes in breeding status (e.g. vocal activity decreasing after pairing, Gil *et al.* 1999, Amrhein

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et al. 2002) or to establish and maintain territory boundaries, in which case vocal activity remains more or less constant during the breeding season (Liu 2004, Catchpole & Slater 2008). Similarly, nocturnal vocal activity of usually diurnal birds is often related to mate attraction (reviewed by La 2012). Therefore, studying diel and seasonal changes in vocal activity of birds has helped elucidate the function of bird vocalizations and broaden our knowledge on ecology and breeding phenology (Amrhein *et al.* 2002, Gil & Llusia 2020).

Although bird vocal activity has attracted the attention of ornithologists for centuries (e.g. Rhoads 1889), the main causes of diel and seasonal changes in avian vocal activity remain unclear and seem to differ among species (Staicer *et al.* 1996, Catchpole & Slater 2008). Furthermore, most bird species are able to produce different types of vocalizations (e.g. different song types, territorial calls and warning calls) (Catchpole & Slater 2008). The origin and evolution of different bird vocalizations may differ and, consequently, the function and seasonality of vocal activity may differ even within species according to the vocalization type analysed (see Staicer *et al.* 1996, Pérez-Granados *et al.* 2018). Most previous research on seasonal changes in vocal activity in birds has used northern temperate passerines as case study species (reviews in Catchpole & Slater 2008, Gil & Llusia 2020), and information about seasonal changes in vocal activity in tropical birds is sparse.

Cuckoos (Cuculidae) are obligate avian brood parasites that do not provide parental care (Davies 2000). Study of the vocal activity of cuckoos is interesting, as song function and communication roles described for most bird species cannot be extrapolated to cuckoos due to their parasitic breeding system. Moreover, the study of the vocal behaviour of cuckoos may provide valuable information about their breeding phenology (Yoo *et al.* 2020). Our current knowledge about seasonal changes in the vocal activity of cuckoos is restricted to that obtained by monitoring the Common Cuckoo *Cuculus canorus* and the Lesser Cuckoo *Cuculus poliocephalus* over 5 months in Korea (Yoo *et al.* 2020). Recent studies have used passive acoustic monitoring as a tool to monitor the vocal activity of cuckoos (Huang *et al.* 2017, Deng *et al.* 2019, Yoo *et al.* 2020). However, the effectiveness of automated signal recognition software for monitoring avian brood parasites has not

yet been tested. Several cuckoos have characteristic and monotonous songs, perhaps making them suitable for automated signal recognition analysis.

In this study, we aimed to monitor the seasonality of two different vocalizations of a Neotropical cuckoo, the Striped Cuckoo *Tapera naevia*, over a complete annual cycle. We chose the Striped Cuckoo because it is a shy but common bird in the Brazilian Pantanal, and there is very limited information about its ecology and vocal behaviour. Furthermore, the Striped Cuckoo produces different types of vocalizations, making it an interesting case study to look for seasonal variation in the delivery of different vocalization types in tropical birds. Our specific objectives were: (1) to evaluate the use of passive acoustic monitoring coupled with automated signal recognition to monitor its vocal behaviour; (2) to determine whether the patterns of vocal activity vary between the two main vocalization types (*sem-fim* and *wee-series* songs); and (3) to improve our knowledge about the ecology of the species and propose the most effective sampling periods for future monitoring programmes. Although vocalization functions cannot be demonstrated without experimental or observational studies, we hypothesized that if the vocalization types of the Striped Cuckoo have different functions, their diel and seasonal patterns would differ. The *sem-fim* song is uttered by Striped Cuckoos singing alone and repeated all day and night, whereas the *wee-series* song is usually emitted by birds countersinging with neighbours and responding to playback (Smith & Smith 2000, see Study species section). We thus assumed that the *sem-fim* song might be related to mate attraction whereas the *wee-series* song may be associated with territorial defence. Previous studies have suggested that females of several cuckoos may be sexually receptive throughout the breeding season (i.e. several months, Payne 1973, Nakamura *et al.* 2005); thus, cuckoo males should keep singing as long as possible to attract additional females (Yoo *et al.* 2020). Following that reasoning, we expected that *sem-fim* singing activity of the Striped Cuckoo would remain constant over a long period of time if it is truly related to mate attraction. In contrast, the *wee-series* singing activity would be much reduced, and concentrated in the period of maximum territorial defence. This prediction is based on previous studies of the Common Cuckoo that found a sharp peak of vocal and territorial activity in the early breeding season,

when males arrived at their breeding grounds and competed for females and to defend territories, decreasing thereafter when territories and/or pair-bonds were established (Riddiford 1986, Yoo *et al.* 2020).

MATERIAL AND METHODS

Study area

This study was carried out in the northeastern Brazilian Pantanal, comprising three acoustic monitoring stations placed around the SESC Pantanal resort (Mato Grosso, Brazil; 16°30′S, 56°25′W). This area is located in the floodplain of the Cuiabá River (Supporting Information Appendix S1), which is seasonally flooded from October to April (Junk *et al.* 2006). The vegetation comprises a mosaic of forest formations and savannas. A detailed description of the vegetation community and the effect of flood seasonality on the local avian community can be found in de Deus *et al.* (2020). The climate is tropical and humid, with average annual rainfall between 1000 and 1500 mm and mean annual temperature of approximately 24 °C (Junk *et al.* 2006). The accumulated rainfall during the monitored annual cycle (June 2015–May 2016, see below) 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). Mean temperature during the studied year was 25.5 °C.

Study species

The Striped Cuckoo is a common inhabitant of open land with scattered trees and thickets from southern Mexico to northern Argentina (Fiorini *et al.* 2019, Lowther 2020). Territorial and solitary individuals form temporary pairs for a few weeks of the year during the breeding period (Mark & Gamez-Rugama 2015). The Striped Cuckoo is shy and elusive, with high vocal activity (Smith & Smith 2000). The vocal repertoire comprises two main types: the *sem-fim* song and the *wee-series* song (Smith & Smith 2000) (Fig. 1; listen an audio file available in Supporting Information Appendix S2). The *sem-fim* song is the most common vocalization and has been defined as a clear and monotonous rising couplet that is sometimes repeated all day and all night (Sick 1953, Smith & Smith 2000) (Fig. 1). This song type is usually produced by birds that are not interacting with other individuals (Smith & Smith 2000, Lowther 2020). The less common *wee-series* song consists of an ascending series of 4–7 *wees* (range 1–16) (Fig. 1), which are usually emitted by birds countersinging with neighbours, engaging with opponents or responding to playback (see playback experiment in Smith & Smith 2000). However, none of the birds that approached the recorders playing back the *wee-series* exhibited attack behaviour; therefore, it has been proposed that *wee-series* is not related to a high probability of fighting (Smith & Smith 2000). The Striped Cuckoo also rarely produces a third type of vocalization, which was not considered in our study, the *feeee* song (Sick 1953, Lowther 2020), apparently occurring only in duets (Smith & Smith 2000). There is no information available about whether female Striped Cuckoos vocalize, and we do not discard this possibility, as both sexes vocalize in other cuckoo species (e.g. Deng *et al.* 2019, Austin *et al.* 2021).
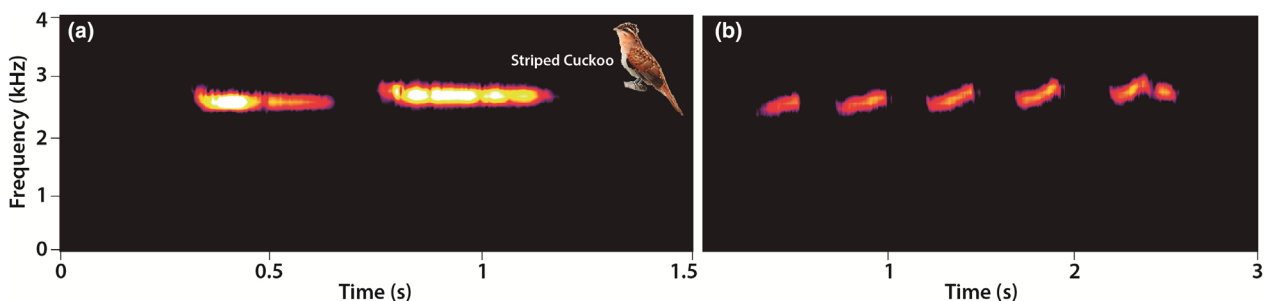

Figure 1. Spectrogram of a typical (a) *sem-fim* and (b) *wee-series* song of the Striped Cuckoo recorded in the Brazilian Pantanal (municipality of Poconé) during the study period with a Song Meter SM2 recorder.

Acoustic monitoring

The three acoustic monitoring stations were separated by a minimum distance of 800 m (range 800–2800 m, Appendix S1). The stations were part of the 'Sounds of the Pantanal – The Pantanal Automated Acoustic Biodiversity Monitoring' project run by the Instituto Nacional de Ciência e Tecnologia em Áreas Umidas and were spatially dispersed to cover the most representative vegetation formations of the Brazilian Pantanal (forest and savannas). One Song Meter SM2 recorder (Wildlife Acoustics, www.wildlifeacoustics.com) was deployed at each acoustic monitoring station and operated daily from 8 June 2015 to 31 May 2016. Previous research has shown that the effective detection radius of the Song Meter SM2 recorder is approximately 150–160 m (Rempel et al. 2013, Pérez-Granados et al. 2019); therefore, the risk of recording the same individual from two different stations was low. The recorders were programmed to record (stereo in .wav format) the first 15 min of each hour during the whole study period, with a sampling rate of 48 kHz and 16 bits per sample. Recorders were checked weekly to download data and change batteries.

Acoustic data analyses

The left channel of the recordings was scanned with Kaleidoscope Pro 5.1.9h (hereafter Kaleidoscope). Kaleidoscope can be configured to scan recordings for signals based on minimum and maximum frequency range (Hz), minimum and maximum signal length (s), and maximum intersyllable gap (ms). The maximum intersyllable gap is defined as the maximum allowable gap between syllables to be considered part of the same vocalization (e.g. sounds separated by less time than the introduced parameter will be considered to be part of the same sound). To calibrate these parameters in Kaleidoscope, we analysed 40 sem-fim songs and 30 wee-series songs recorded in the study area using Song Meter SM2 recorders (Fig. 1, Appendix S2). The vocalizations were measured from spectrograms in Raven Pro 1.5 (Bioacoustics Research Program 2014). Both vocalizations had similar acoustic measurements (Supporting Information Appendix S3) and hence the same parameters were used to detect both types of vocalizations. We chose the minimum and maximum values of the frequency range (2100 and

3400 Hz, respectively) and call length (0.5 and 6 s, respectively) to maximize the possibility of detecting the vocalizations of the species, recognizing that this will also lead to a greater number of false detections. Maximum intersyllable gap was 0.4 s, enabling us to identify entire sem-fim and wee-series vocalizations, which are composed of different syllables, as single vocalizations (Fig. 1). We scanned all the recordings with Kaleidoscope and detected all candidate sounds that satisfied the search criteria.

In a second step, candidate sounds were grouped using the cluster analysis function in Kaleidoscope. First, the software extracted the discrete cosine transform (DCT) coefficients of the spectrum of the candidate sounds, and a hidden Markov model was constructed from the vector of the DCT of each candidate sound. The vectors were clustered using K-Means clustering. Vocalizations were included in existing clusters if they were within some minimum distance of the cluster, or otherwise a new cluster was formed. Candidate sounds within clusters were sorted by similitude, and thus most of the signals in a cluster belonged to a particular vocalization type of the same species, and the first sounds of each cluster were the most similar to each other and the most representative of that cluster. An additional parameter required by Kaleidoscope is the 'maximum distance from cluster centre to include outputs'. This parameter can range between 0 and 2, with larger values capturing more candidate sounds, which will inevitably include progressively more non-target signals (Pérez-Granados et al. 2020). We set this value to 2, as we wanted to minimize overlooking Striped Cuckoo vocalizations. In the last step, each cluster automatically created by Kaleidoscope was manually labelled as 'sem-fim', 'wee-series' or 'other sounds' according to whether there was a sem-fim or a wee-series song within the first 50 candidate sounds of each cluster (see a similar approximation in Pérez-Granados & Schuchmann 2020, 2021a). The sounds within the cluster 'other sounds' were not checked and were excluded from subsequent analyses. Finally, every candidate sound within the clusters labelled 'sem-fim' or 'wee-series' was visually and/or acoustically checked, always by the same observer, to separate target signals from non-target signals.

We assessed the performance of the cluster analysis function (hereafter referred to as the recognizer) by measuring precision, recall and the F-

score (Knight *et al.* 2017). Precision was estimated by dividing the total number of target vocalizations by the total number of candidate sounds within a cluster (Pérez-Granados & Schuchmann 2020, 2021a). Recall represents the proportion of target vocalizations that were detected by the recognizer (Knight *et al.* 2017), here calculated by dividing the total number of *sem-fim* (or *wee-series*) songs detected by Kaleidoscope by the total number of *sem-fim* (or *wee-series*) songs captured on the recordings (Knight *et al.* 2017). The total number of both types of vocalizations per recording was annotated by the same experienced observer after visually and acoustically checking 228 selected recordings of 15 min duration. We reviewed a total of 60 recordings with the known presence of *sem-fim* songs and 60 recordings with the known presence of *wee-series* songs according to Kaleidoscope (30 recordings per vocalization type and occupied station, see Results) and 108 randomly selected recordings (four recordings per station and month) recorded between June and February between 05:00 and 07:00 h, when the singing activity of the species was at its maximum (see Results). Recordings were reviewed blinded with respect to station identification, date of recording and whether the species had been detected by Kaleidoscope. The *F*-score is a metric that combines precision and the recall rate into a single metric. It is calculated as $((\beta^2 + 1) * \text{precision} * \text{recall})/(\beta^2 * \text{precision} + \text{recall})$ (see Knight *et al.* 2017); β is a predefined metric that allows for prioritization of precision over recall rate. We used a value of $\beta = 1$, weighting recall rate and precision equally.

Statistical analyses

To determine whether vocal activity varied with time of day, we fitted independent generalized linear models (GLMs) for each vocalization type. We fitted a GLM (quasibinomial error structure) using the percentage of *sem-fim* (or *wee-series*, with respect to the total) songs detected per hour in each month as the response variable and recording hour and station as factors. Those months with fewer than 10 vocalizations (see Results) were not included in the analyses to reduce the number of levels per factor. We also fitted an independent GLM (Poisson error structure) to identify the months with significantly high vocal activity for each vocalization type. In the GLM, we introduced the daily number of *sem-fim* (or *wee-series*) vocalizations detected as the response variable and month and station as factors. Those months with fewer than 10 vocalizations were not included in the analyses. Station was not included as a random effect due to the small number of levels within the factor (two stations); a minimum of five levels are recommended to consider a factor random (Harrison 2015). When the factor Month was found to be significant, a Tukey's post-hoc test was performed to test for differences among the levels of the factor. All statistical analyses were performed with R 3.6.2 (R Development Core Team 2019). We used the package 'multcomp' (Hothorn *et al.* 2008) for post-hoc comparison tests. The level of significance was set at $P < 0.05$.

RESULTS

The initial filtering in Kaleidoscope produced a total of 1 192 347 candidate sounds, of which 1 142 230 were within the cluster 'other sounds', 37 776 within the cluster '*sem-fim*', and 12 341 within the cluster '*wee-series*'. The precision of the recognizer for the *sem-fim* song was 14.0%, as 5295 *sem-fim* songs were detected within the 37 776 candidate sounds in the cluster '*sem-fim*', and the precision of the recognizer for the '*wee-series*' song was 4.7% (580 *wee-series* vocalizations detected among the 12 341 candidate sounds in the cluster '*wee-series*'). Most of the misclassified sounds in the '*sem-fim*' and '*wee-series*' clusters were sounds of a cricket producing sound with a frequency and structure to that of Striped Cuckoo vocalizations. There were also numerous vocalizations of the Chaco Chachalaca *Ortalis canicollis* and the Pale-legged Hornero *Furnarius leucopus*. The recall rate of the recognizer of the *sem-fim* song was 73.2% (903 *sem-fim* songs detected by Kaleidoscope among 1232 *sem-fim* songs annotated in the 228 recordings in the validation dataset), and the recall rate of the *wee-series* song was 80.1% (214 *wee-series* songs automatically detected among 267 annotated in the validation data set). The *F*-scores were 0.23 and 0.09 for the *sem-fim* and *wee-series* songs, respectively. Striped Cuckoos were detected at two of the three acoustic monitoring stations, and the number of vocalizations detected per station ranged between 3548 and 2327. Overall, a total of 5295 *sem-fim* and 580 *wee-series* songs were detected.

Diel activity pattern

The diel pattern of vocal activity differed greatly between the two vocalization types (Fig. 2). *Sem-fim* song production varied through the course of the day (Table 1). The maximum number of *sem-fim* songs was detected in the hours following sunrise (37.4% of total calls detected between 05:00 and 08:00 h), with a second peak of activity just before dusk (13.4% of total calls detected between 16:00 and 17:00 h, see Supporting Information Appendix S4 for hourly production at each station). High *sem-fim* singing activity was also

detected in the middle of the night, with 13.2% of the calls detected between 00:00 and 01:00 h (Fig. 2, Appendix S4). *Wee-series* song production was almost entirely restricted to the daytime period, with only three songs detected between 18:00 and 04:00 h (Fig. 2, Supporting Information Appendix S5 for hourly production at each station). The *wee-series* song showed a bimodal pattern, with the first peak of activity around sunrise (34% of the *wee-series* songs were detected between 05:00 and 06:00 h) and a second peak of activity at 17:00 h, when 20.5% of the *wee-series* songs were detected (Fig. 2).
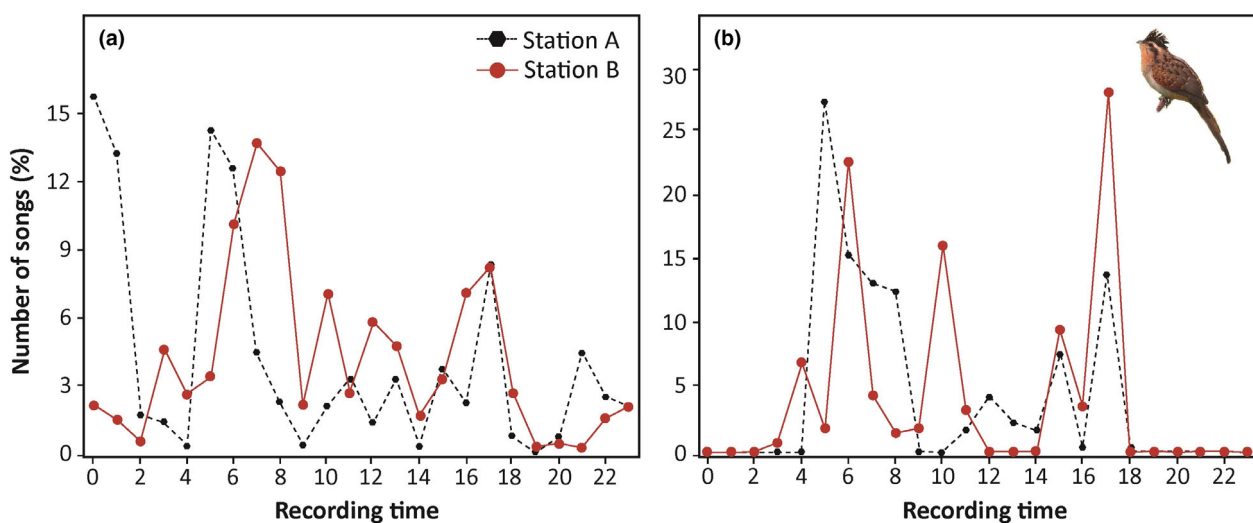

Figure 2. Diel singing activity pattern of the Striped Cuckoo. Singing activity is shown separately for the two main vocalizations of the species: the *sem-fim* song (a) and the *wee-series* song (b). Singing activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at three acoustic monitoring stations, although the species was detected in only two of them. The diel pattern of each vocalization refers to the percentage of calls detected during each recording time per station. Hours are expressed in winter local time (UTC −4).

Table 1. Summary table of type-III variance partitioning performed to test the effects of recording time and month on the *sem-fim* and *wee-series* singing activity of the Striped Cuckoo. 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, although the species was detected at two stations.

Variable	Vocalization	Variable	df	sd Resid.	df Resid.	sd	F	P
Recording time	*Sem-fim*	*Hour*	23	9.26	312	30.27	3.24	<0.001
		Station	1	0	311	30.27	0.01	0.990
	Wee-series	*Hour*	23	13.29	120	13.71	4.86	<0.001
		Station	1	0	119	13.71	0.01	0.998
Month	*Sem-fim*	*Month*	7	2499.6	480	16 508	357.1	<0.001
		Station	1	294.1	479	16 213	294.1	<0.001
	Wee-series	*Month*	4	736.8	301	2168.3	184.2	<0.001
		Station	1	3.76	300	2164.6	3.756	0.0526

Seasonal activity pattern

The singing activity of the Striped Cuckoo showed clear seasonality (Fig. 3). The species was detected for the last time on 8 January at Station A and 12 February at Station B despite continuous monitoring through to 31 May at both stations (Table 2). Production of *sem-fim* songs extended from mid-June to mid-February, with the number of *sem-fim* songs detected varying substantially over the months (Table 1). Maximal *sem-fim* production occurred between July and October, a period during which 78.8% of the total *sem-fim* songs were detected (Fig. 3, see Supporting Information Appendix S6 for monthly production at each station). October was the month with the largest number of *sem-fim* songs detected (25.6%) and the month with significantly high *sem-fim* singing activity according to Tukey's post-hoc test (Supporting Information Appendix S7). A second and small peak of *sem-fim* singing activity occurred during December (11.7% of the calls). The *wee-series* song was detected from late July to mid-February and showed more marked seasonality than the *sem-fim* song, with 90% of the *wee-series* songs being detected in September and October (Fig. 3, see Supporting Information Appendix S8 for monthly production at each station). September was the month with the largest number of *wee-series* songs detected (55.3%) and the month with significantly high *wee-series* singing activity according to Tukey's post-hoc test (Supporting Information Appendix S9).

DISCUSSION

In this study, we quantified the diel and seasonal changes in the two main vocalization types of the
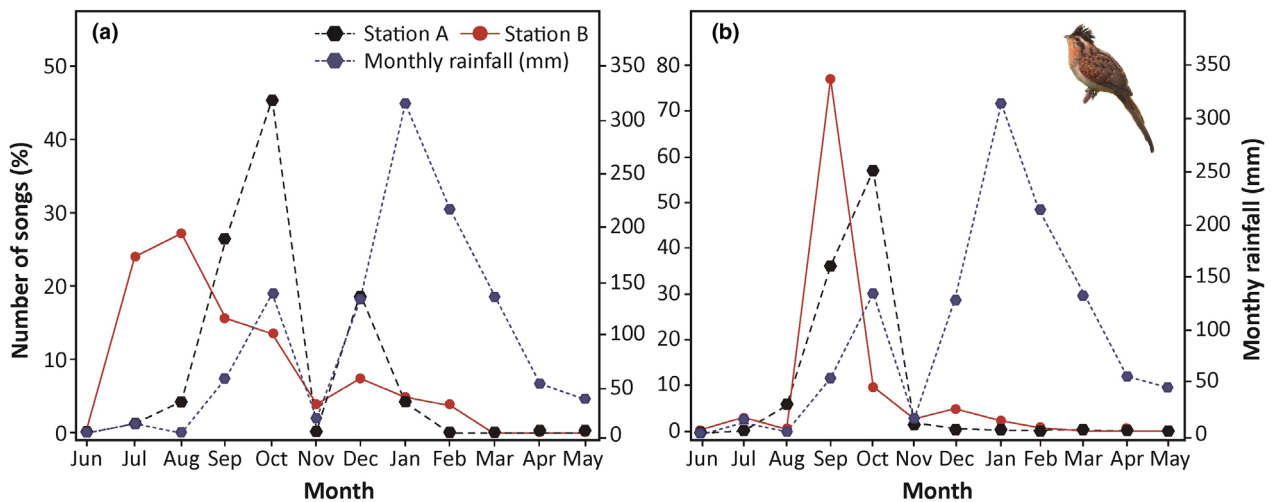

Figure 3. Seasonal singing activity pattern of the Striped Cuckoo. Singing activity is shown separately for the two main vocalizations of the species: the *sem-fim* song (a) and the *wee-series* song (b). The seasonal pattern is expressed as the percentage of calls detected during each month per station (left *y*-axis). Monthly accumulated rainfall (mm) (blue circles) according to a weather station in the study area is shown on the right *y*-axis.

Table 2. Summary of vocal activity of the Striped Cuckoo over an annual cycle. Vocal activity is shown separately for the *sem-fim* and *wee-series* songs of the species. Vocal activity was monitored using autonomous recording units from 8 June 2015 to 31 May 2016 at three acoustic monitoring stations, although the species was detected at only two stations. Hours are expressed as coordinated universal time (UTC) −4.

Vocalization	Station	First song	Last song	Most active day	Most active hour	Most active month	Days detected
Sem-fim	A	20 July	8 January	28 July	00:00	October	60
	B	10 June	12 February	12 December	07:00	August	110
Wee-series	A	13 August	10 December	15 September	05:00	October	29
	B	24 July	10 February	8 October	17:00	September	25

Striped Cuckoo over a complete annual cycle. Both vocalization types showed different diel and seasonal patterns that suggest that *sem-fim* and *wee-series* songs may have different functions. Although the function of a vocalization cannot be demonstrated without experimental or observational studies, the patterns found in this study provide some useful insights. The relatively constant seasonal pattern of the *sem-fim* song between July and October suggests that this vocalization might be related to mate attraction, in agreement with the hypotheses that cuckoo males should vocalize over long periods of time to attract additional females (Yoo *et al.* 2020) since female cuckoos can be fertile for several months (Payne 1973, Nakamura *et al.* 2005). Similarly, in multi-brooded passerines, vocalizations related to mate attraction are also maintained during the breeding season, which has been proposed as a response to maintain pair bonds and quickly mate between successive clutches, or if the nest is predated (e.g. Mace 1986, Pärt 1991). In contrast, the more marked seasonal pattern of the *wee-series* song suggests that this vocalization plays a role in territorial defence (90% of the calls were produced within a period of 2 months). This pattern is consistent with previous findings for the Common Cuckoo (Riddiford 1986, Yoo *et al.* 2020), showing high vocal and territorial activity in the early breeding season, when males arrive at their breeding grounds to compete for females and defend territories, and decreasing thereafter. We did not detect any Striped Cuckoo vocalizations between mid-February and June, although we did opportunistically detect the species <50 km from the study area during this period. This suggests that the species might be partially migratory, leaving the region when it is seasonally flooded from February onwards (de Deus *et al.* 2020). This might also partly explain the high *wee-series* singing activity once males return to the study area and must compete to set up territories and attract females. We found a second peak of *sem-fim* but not *wee-series* singing activity in December. This peak of vocal activity after the breeding period might be related to the observations made by Mark and Margez-Raguma (2015), who found that juveniles were often associated with adult conspecifics after the breeding period and that adult Striped Cuckoos engaged in *sem-fim* but not *wee-series* duets after the breeding period. Such contact might be relevant to the development of social communication and sexual preferences in young cuckoos (Mark & Gamez-Rugama 2015).

At the daily scale, both song types showed a bimodal pattern, with the first peak of vocal activity after sunrise and the second peak at sunset, which is in agreement with the typical diel pattern described for most bird species, including cuckoos (Huang *et al.* 2017, Deng *et al.* 2019, Yoo *et al.* 2020). However, whereas the production of *sem-fim* songs extended into the night, the *wee-series* songs were restricted to the diurnal period. The nocturnal *sem-fim* singing activity of the Striped Cuckoo is in agreement with a previous description of the vocal behaviour of the species (Smith & Smith 2000, Lowther 2020) and with prior research that also found that many cuckoos may vocalize at night (e.g. Huang *et al.* 2017, Deng *et al.* 2019, Yoo *et al.* 2020). The nocturnal *sem-fim* singing activity agrees with the assumption that this song type might be related to mate attraction, following the hypotheses proposed for nocturnal singing in several diurnal passerines (La 2012). However, our current knowledge about nocturnal singing of diurnal birds is scarce and mostly limited to temperate passerines (e.g. Amrhein *et al.* 2002, La 2012, Kułaga & Budka 2020, but see Pérez-Granados & Schuchmann 2021b); therefore, further research is required to elucidate the functionality of nocturnal vocalizations in the Striped Cuckoo and other cuckoos (Deng *et al.* 2019, Yoo *et al.* 2020). Further experimental tests, such as simulating intruders using playback, could shed light on the specific functions of the *sem-fim* and *wee-series* songs in the Striped Cuckoo, and ideally also elucidate the function of the third vocalization of the species, the *feeee* song.

Our findings also shed light on the breeding schedule of this species in the Brazilian Pantanal. Based on seasonal changes in vocal activity, breeding seems to commence at the end of the dry season (August–October), coinciding with a period of high food abundance in the Brazilian Pantanal (Marques *et al.* 2010, 2011) driven by the onset of rainfall (which occurred in September during the monitored annual cycle, Fig. 3), leading to elevated insect and fruit abundance (Wolda 1978, Ragusa-Netto 2015). This proposed breeding period aligns with the nesting period for most passerine birds, the hosts of the species, which breed between August and November in the study area (e.g. Bouton *et al.* 2005, Pinho & Marini 2014). Our results also suggest that acoustic surveys to

detect the species are best performed in the early hours after sunrise during September and October.

One of the main advantages of passive acoustic monitoring is that it enables simultaneous sampling over large temporal and spatial scales. However, the use and validation of automated signal recognition software is required to obtain robust conclusions from long-term field recordings (e.g. Knight *et al.* 2017, Knight & Bayne 2019, Pérez-Granados & Schuchmann 2020). In this study, we have shown that automated signal recognition is a reliable tool for monitoring avian brood parasites. Kaleidoscope Pro was able to detect 78–84% of each vocalization type of the target species. These values can be considered high and are similar to previous studies that used the same automated recognition software for monitoring seven bird species in the study area (range 71–85%, see Pérez-Granados & Schuchmann 2021a). However, the precision of the recognizers was very low (5–14%). The low recognizer precision had no effect on our results, as every candidate sound was manually verified, but it may reduce the utility of passive acoustic monitoring in larger studies. The creation of more advanced classifiers using machine-learning or convolutional neural networks might be useful for creating classifiers with greater precision, thereby reducing the number of misclassified sounds (LeBien *et al.* 2020).

Passive acoustic monitoring coupled with automated signal recognition has revealed the diel and seasonal variation in vocalizations of a Neotropical cuckoo, an ecological pattern that would be very difficult to ascertain using traditional field methods. Our study provides a case study of using automated signal recognition in ornithological studies, and it may prove especially useful for deeper study of vocal and reproductive behaviours in brood parasitic cuckoos.

AUTHOR CONTRIBUTIONS

Cristian Pérez-Granados: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review & editing (equal). **Karl-L. Schuchmann:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal).

CONFLICT OF INTEREST

None.

ETHICS STATEMENT

This study is part of the biodiversity monitoring project Sounds of the Pantanal–The Pantanal Automated Acoustic Biodiversity Monitoring of INAU/CO.BRA, Cuiabá, Mato Grosso, Brazil, which was conducted under SISBIO permit no. 39095 (KLS).

Data Availability Statement

Number of Striped Cuckoo songs detected per hour and month at each acoustic monitoring station can be found in the Supporting Information. Data employed for statistical analyses can be found at https://figshare.com/s/2e7d514a8c14e789104b. DOI: 10.6084/m9.figshare.19387112

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Supporting Information