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Passive Acoustic Monitoring of Chaco Chachalaca (*Ortalis canicollis*) Over a Year: Vocal Activity Pattern and Monitoring Recommendations

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Abstract

Chaco Chachalaca (*Ortalis canicollis*) is a declining Neotropical bird, for which our current knowledge about its natural history is very limited. Here, we evaluated for first time the utility of passive acoustic monitoring, coupled with automated signal recognition software, to monitor the Chaco Chachalaca, described the vocal behavior of the species across the diel and seasonal cycle patterns, and proposed an acoustic monitoring protocol to minimize error in the estimation of the vocal activity rate. We recorded over a complete annual cycle at three sites in the Brazilian Pantanal. The species was detected on 99% of the monitoring days, proving that this technique is a reliable method for detecting the presence of the species. Chaco Chachalaca was vocally active throughout the day and night, but its diel activity pattern peaked between 0500 and 0900. The breeding season of Chaco Chachalaca in the Brazilian Pantanal, based on seasonal changes in vocal activity, seems to occur during the last months of the dry season, with a peak in vocal activity between August and October. Our results could guide future surveys aiming to detect the presence of the species, both using traditional or acoustic surveys, or to evaluate changes in population abundance using passive acoustic monitoring, for which recorders should be left in the field for a minimum period of nine days to obtain a low-error estimate of the vocal activity of the species. Our results suggest that passive acoustic monitoring might be useful, as a complementary tool to field studies, for monitoring other cracids, a family with several threatened species that are reluctant to human presence.

Keywords

cracidae, *kaleidoscope*, *neotropics*, *pantanal*, seasonality, vocal behavior, wildlife monitoring

The family Cracidae is composed of 50 medium- to large-sized arboreal birds and is one of the largest Neotropical families of frugivorous birds (Muñoz & Kattan, 2007; Fleming & Kress, 2011). Among cracids, Chaco Chachalaca (*Ortalis canicollis*), the smallest of its genera (500–700 g), has a distribution range restricted to southwestern Brazil, eastern Bolivia, western Paraguay, and northern Argentina (del Hoyo & Kirwan, 2020). It is a common resident and frugivorous species typically found in pairs or groups as large as 30 birds. It inhabits lowland dry and semideciduous forests, such as the *Chaco* and the *Cerrado* (del Hoyo & Kirwan, 2020). Previous studies have suggested that Chaco Chachalaca may play an important role as a seed disperser since individuals pass intact seeds through the digestive tract; therefore, the species could be used as an indicator species of

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ecosystem quality (Caziani & Protomastro, 1994; Ragusa-Netto, 2015). Our current knowledge about the natural history of the species is almost entirely restricted to its diet and feeding ecology, which is mainly composed of leaves, fruits, flowers, and eventually arthropods (see Caziani & Protomastro, 1994; de Paiva et al., 2013; Ragusa-Netto, 2015). There is little information available on other ecological traits of the species, such as its vocal behavior and breeding ecology, (but see del Hoyo & Kirwan, 2020). Nonetheless, previous studies have found definite diel patterns of vocal activity of several cracids, with peaks of vocal activity around dawn and in late afternoon (Hayes et al., 2009; Baldo & Mennill, 2011), as well as seasonal patterns of vocal activity that may differ among species (Begazo & Bodmer, 1998; Baldo & Mennill, 2011).

Chaco Chachalaca is considered a common bird species in its distribution range, and it is cataloged as the least conservation concern by the IUCN Red List (BirdLife International, 2016). However, the population size of the species has declined with known cases of local and regional extinctions in recent decades, mainly due to habitat loss, hunting, and being kept as cagebirds (Silva & Strahl, 1991; BirdLife International, 2016; 2020). Currently, no systematic monitoring scheme has been developed for this species (BirdLife International, 2016). Therefore, it is advisable to increase our knowledge about the ecology of the species and develop effective monitoring protocols to assess future population trends to contribute to adequate conservation and management strategies.

Chaco Chachalaca is thought to vocalize mainly during the first hours of the day, although there are no quantitative studies about the vocal behavior of the species (del Hoyo & Kirwan, 2020). The main vocalization of the species (call hereafter) consists of a short series of harsh, raucous syllables transcribed as "Chata-ra-ta" (del Hoyo & Kirwan, 2020) (Figure 1). Vocal activity is usually initiated by males from trees, and commonly other birds within the group or neighboring groups answer (del Hoyo & Kirwan, 2020). The call of the Chaco Chachalaca is loud and uttered at low frequencies (Figure 1), which makes it audible by humans at distances as great as 500 m (del Hoyo & Kirwan, 2020). These particularities suggest that the use of passive acoustic monitoring might be a reasonable technique to monitor the presence and ecology of the species. Indeed, previous studies have employed this method for monitoring cracids, such as curassows and guans (Baldo & Mennill, 2011; Maia et al., 2019). However, to our knowledge, no published study has assessed the utility of signal recognition software for automatically detecting the call of any cracid, which may enhance the application of sound recorders for monitoring cracids at large spatial and temporal scales.

In this study, we employed passive acoustic monitoring over a complete annual cycle at three acoustic monitoring stations to monitor the vocal behavior of Chaco Chachalaca in the Brazilian Pantanal. We selected Chaco Chachalaca as the study model because (1) it is locally abundant in the Brazilian Pantanal (de Paiva et al., 2013; Nunes, 2015); (2) the species is expected to play an important role in forest regeneration (Ragusa–Netto, 2015); and (3) the population size of the species are decreasing, and further knowledge about its biology and monitoring protocols is desirable. Our specific goals were to (1) evaluate passive acoustic monitoring as a feasible technique to monitor the presence and vocal behavior of a cracid for the first time; (2) describe and analyze the patterns of diel and annual variations in vocal activity of Chaco Chachalaca to gain insights into the ecology of the species and propose effective sampling periods for monitoring the species; and (3) develop a species-specific effective monitoring protocol to monitor the Chaco Chachalaca using passive acoustic monitoring, in which we estimated the minimum number of recording days needed to estimate a reliable detected vocal activity rate (DVAR hereafter) for this species. The DVAR, defined as the number of vocalizations detected per unit time of recording, is an acoustic index that has proven to be useful to estimate bird density around recorders for a large number of bird species (reviewed by Pérez–Granados & Traba, 2021). The basic assumption is that the number of vocalizations of a target species on sound recordings should be correlated with the density of the species around recorders. Therefore, once the relationship between DVAR and bird density is known, it could be used to predict bird density around recorders. However, DVAR may greatly differ among successive days and recording over a large number of monitoring days might be required.

Methods

Study Area

The study was carried out in the northeastern part of the Brazilian Pantanal. The investigated area comprised three acoustic monitoring stations placed around the SESC Pantanal (Serviço Social do Comércio, SESC, Poconé, Mato Grosso, Brazil; 16°30S, 56°25′W, Supplemental Figure S1), which is located within the floodplain of the Cuiabá River, one of the main tributaries of the Paraguay River. The study area is seasonally inundated from October to April due to flooding of the Paraguay River (Junk et al., 2006). The dominant vegetation is a mosaic of different forest formations and savannas. Detailed information about the vegetation community and the effect of flood seasonality in the avian community in the study area can be found in de Deus et al. (2020). The regional climate is tropical and humid, with a mean annual temperature of approximately 24°C and an average annual rainfall ranging between 1000 and 1500 mm (Junk et al., 2006). The mean annual temperature during the monitored annual cycle (June 2015–May 2016, see below), based on weather data collected from a meteorological station located in the study area, was 25.5°C, while the accumulated annual rainfall was 1131 mm, which followed the typical rainfall regime of the Brazilian Pantanal (1025 mm accumulated during the wet season, October–April, Pérez-Granados & Schuchmann, 2020a).

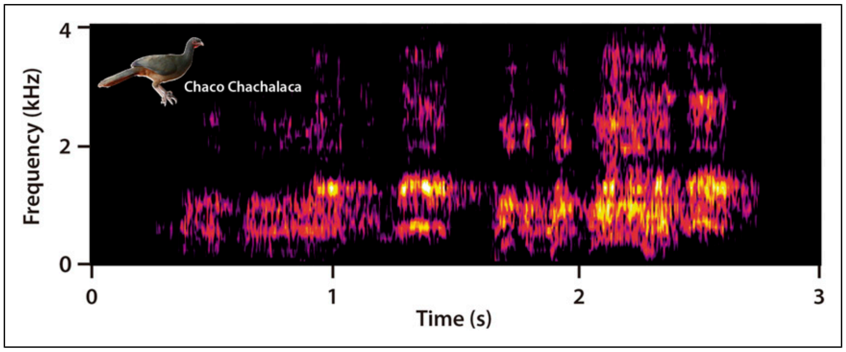

Figure 1. Spectrogram of a typical call of the Chaco Chachalaca in the Brazilian Pantanal.

Acoustic Monitoring

The three acoustic monitoring stations were separated by a minimum distance of 1300 m (range 1300–2900 m, Supplemental Figure S1). One Song Meter SM2 recorder (Wildlife Acoustics, www.wildlifeacoustics.com) was deployed at each acoustic monitoring station and remained active and in the same location from June 8, 2015 to May 31, 2016. The recorders were programmed to record (in stereo and .wav format) the first 15 min of each hour (24 hours per day) using a sampling rate of 48 kHz and 16 bits per sample. The recordings were stored on SD memory cards, and the recorders were checked weekly to download data and change batteries. Although we do not have field observations of field studies about the distance at which Chacho Chachalaca vocalizations can be recorded with Song Meter SM2 recorders, according to the large distance among acoustic monitoring stations (minimum of 1300 m), we consider that the risk of recording the same individual from two different stations should be low (Rempel et al., 2013; Pérez-Granados et al., 2019a).

Acoustic Data Analyses

The left channel of the recordings was scanned using Kaleidoscope Pro 5.1.9 h (Kaleidoscope hereafter), which is an automated signal recognition software developed by Wildlife Acoustics (www.wildlifeacoustics.com) for the efficient processing and analysis of acoustic recordings. Kaleidoscope can scan the recordings and report only those sounds that meet the criteria introduced in the signal parameters, which are as follows: minimum and maximum frequency ranges (Hz), minimum and maximum lengths of detection (s), and maximum intersyllable gap (ms). The maximum intersyllable gap is defined as the maximum allowable gap between syllables to be considered as a part of the same vocalization. Therefore, sounds separated by less time than the introduced parameter will be considered to be part of the same sound. First, we characterized 47 calls of the Chaco Chachalaca according to a set of parameters (Supplemental Table S1), recorded in the three monitored acoustic monitoring stations and using the same recorder, to introduce accurate signal parameters in Kaleidoscope (Supplemental Table S1). Recordings were part of the INAU Pantanal BioData Center (IBPC), a server-based data bank of animal audio from the Pantanal. The acoustic measurements of the calls were measured from spectrograms using Raven Pro 1.5 (Bioacoustics Research Program, 2014). According to our results (Supplemental Table S1), we considered the following values for the signal parameters in Kaleidoscope: minimum and maximum frequencies (300 and 2500 Hz, respectively), minimum and maximum lengths of detection (0.5 and 20 s, respectively, to detect overlapping individuals), and maximum intersyllable gap (0.1 s). This intersyllable gap allowed us to identify successive calls uttered by the species as a single call (Figure 1).

The Kaleidoscope workflow can be separated in three steps: (i) detection of candidate sounds, (ii) grouping of candidate sounds in clusters composed of sounds of high similarity, and (iii) verification of the candidate sounds to remove false positives (detections mislabeled). As indicated, in the first step, Kaleidoscope scanned the whole acoustic dataset and detected all candidate sounds within the introduced signal parameters. Second, the candidate sounds were automatically grouped into clusters by applying the cluster analysis function of Kaleidoscope. Kaleidoscope estimates the discrete cosine transform coefficients (DCTs) of the spectrum of the candidate sounds and fits a hidden Markov model based on the vector of the DCTs of the candidate sounds. These vectors are clustered using K-means clustering, and finally, in the visible output of the software, the candidate sounds appear grouped into groups of similar sounds called "clusters." Clusters are formed by moving candidate sounds to existing clusters if they are within some "distance to cluster center" (i.e., they are grouped together if they are similar enough); otherwise, new clusters are created. This parameter was set to 0.5 (recommended value by default). Larger values may imply a lower number of clusters created and more diverse songs grouped in the same cluster. Similarly, candidate sounds are ordered within clusters by similitude. Therefore, most of the signals of each cluster belong to the same type of sound (e.g., a vocalization of the same species, raining), and the first sounds of each cluster are the most similar and the most representative of this cluster. An additional parameter required by Kaleidoscope to perform the analyses is the "maximum distance from the cluster center to include outputs." We used the maximum allowed distance from the cluster center (value of 2), which maximized the number of calls detected but also increased false positives (Pérez–Granados et al., 2020), as we wanted to prioritize detecting all candidate vocalisations over precision at this stage.

In the third step, each cluster automatically created by Kaleidoscope was manually labeled into two categories: "Target species" or "other sound" according to whether there was a call of the target species within the first 50 candidate sounds of each cluster (see a similar approximation in Pérez-Granados & Schuchmann, 2020a, 2020b). Every candidate sound within the category "Target species" was visually and/or acoustically checked, always by the same observer (CPG), to separate false positives from true positives (correct classifications). A previous study, also in the Brazilian Pantanal using two bird species and following the same approach, found that the % of vocalizations of the target species within the cluster "other sounds" (i.e., false-negative rate) would be around 0.015–0.09% (Pérez-Granados & Schuchmann, 2020a). Therefore, the sounds within the category "other sounds" were not checked and were excluded from posterior analyses.

We evaluated the performance of the cluster analysis function applied by Kaleidoscope (recognizer hereafter) by measuring the precision, the recall rate and the F-score of the recognizer (Knight et al., 2017). The precision is defined as the proportion of sounds detected by the recognizer that are true detections of the target species and is calculated as TP/(TP+FP), where TP is the number of true positivies (detections of the Chaco Chachalaca) and FP is the number of false positives (Knight et al., 2017). We estimated the precision by dividing the total number of Chaco Chachalaca calls detected by the total number of candidate sounds within the cluster "Target species" (Knight et al., 2017; Pérez-Granados & Schuchmann, 2020a). The recall rate is defined as the proportion of target sounds (i.e., Chaco Chachalaca calls in our case) detected by the recognizer, and is calculated as TP/(TP+FN), where FN is the number of false negatives (number of calls of the Chaco Chachalaca not detected by the recognizer) (Knight et al., 2017). We estimated the recall rate of the recognizer by dividing the total number of calls of the Chaco Chachalaca detected by Kaleidoscope by the total number of calls within the sound recordings (Knight et al., 2017; Pérez-Granados & Schuchmann, 2020a). The total number of calls of the species per recording (recording defined as the .wav file of 15 minute period) was always counted by the same experienced observer (CPG) by visually and acoustically checking 200 selected recordings. We reviewed a total of 100 recordings with known presence of the species (according to Kaleidoscope results, one-third of the recordings per site) and 100 recordings randomly selected among those recorded between 0700 and 0800 during the period August–October, the period during which the vocal activity of the species was maximized (see results) and therefore the period with a higher probability of finding recordings indicating the presence of the species. Recordings were reviewed blindly 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 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 priorization of precision over recall rate. We used a value of $\beta = 1$ implying that recall rate and precision had the same importance for our study.

Statistical Analyses

To identify whether vocal activity of the Chaco Chachalaca varied over the day and the monitored annual cycle we used the function gam in R to fit a negative binomial generalized additive model (GAM). We chose that approach to be able to model nonlinear patterns as daily or seasonal patterns of vocal activity. The family negative binomial was selected after testing different distribution families (Gaussian, Poisson, quasi-Poisson, zero-inflated Poisson, and negative binomial), and the most appropriate model according to AIC (lower AIC) and visual checking of the residuals (no patterns detected) was retained. The number of calls detected per recording was used as the response variable, while recording hour, month and station were included as predictors. To better capture the nature of the data the predictors recording hour and month were modeled using an independent spline smoothed function for each acoustic monitoring station. This approach is useful for building models able to represent site-specific differences (similar to varying coefficient models or geographic regression models). To account for the necessary smooth pattern in calls over time of day, in that 23:59 and 00:00 should be almost the same once averaged over many days, we considered a cyclic cubic regression spline for the hour of day smooth term. The station was not included as a random effect due to the low number of levels within the factor (three stations), since a minimum number of five levels are recommended to consider a factor as random (Harrison, 2015).

We also estimated the average minimum number of days that the recorders needed to be left in the field to record a reliable (low-error estimate) DVAR of the species. To do this, we created site-specific curves of the coefficient of variation (Reed et al., 2002) (CV hereafter) for all possible permutations of monitoring days during the last 20 days of the month of September, which was the month with the maximum vocal activity of Chaco Chachalaca (see the Results). We estimated the minimum number of days needed to obtain a reliable DVAR by averaging the minimum time estimate per acoustic monitoring station to reach a CV < 20%. We considered that the CV should be lower than 20% to consider the DVAR reliable (low-error estimate) based on prior research using the same approach (Pérez-Granados et al., 2019b) and previous studies that stated that CVs smaller than 20% can be considered acceptable, while estimates with CV > 30% can be considered to have high variability (Patel et al., 2001; Gordón-Mendoza & Camargo-Buitrago, 2015). All statistical analyses were performed with R 3.6.2 (R Development Core Team, 2019). We used the packages "mgcv 1.8–35" for building the gam model (Wood 2011) and "gtools" (Warnes et al., 2018) to obtain the possible permutations from one to 19 monitoring days. Statistical significance was set at 0.05.

Results

Chaco Chachalaca was detected at the three acoustic monitoring stations, and the number of calls detected per station ranged between 28,705 and 47,028. A total of 934,158 candidate sounds matched the signal parameters introduced in Kaleidoscope, of which 793,957 (491 clusters, 93.2% of the total of clusters created) were within the category "other sounds" and 140,201 candidate sounds (27 clusters, 6.8%) were within the category "Target species." Finally, 112,650 calls of Chaco Chachalaca were identified within the candidate sounds of the category "Target species," and therefore, the precision of the recognizer was 80.3% (112,650 calls within the 140,201 candidate sounds). The recall rate of the recognizer was 77.6% (3575 calls detected by Kaleidoscope of the 4604 calls annotated in the 200 15-min recordings of the validation data set), while the F-score was of 0.79.

Vocal Activity Pattern

Chaco Chachalaca vocalized throughout the diel cycle, including during the nocturnal period (Figure 2, see Supplementary Figure S2 for mean percentage of calls detected at each recording hour). However, the species showed a clear unimodal pattern, with 77.5% of the calls detected between 0500 and 0900 and very low vocal activity during the rest of the day (Figure 2, see Supplementary Table S2 for hourly production at each station). The GAM explained 32.2% of the variance of the data and showed that the diel pattern of vocal activity of the Chaco Chachalaca varied among the recording hours in the three acoustic monitoring stations (Table 1), with a peak of vocal activity at approximately 0700 and 0800 in all acoustic monitoring stations (Figure 2). The species was vocally active throughout the year at the three acoustic monitoring stations. Indeed, the species was detected on 1026 of the 1029 monitoring days (99.7%). Despite that continuous vocal activity, the species showed a clear unimodal pattern of vocal activity during the monitored annual cycle with maximum values between the months of August and December, a period during which 66.2% of the total calls were detected (Figure 2 and see Supplemental Table S3 for monthly production at each station). According to the GAM, the vocal activity of the species differed during the year (Table 1), with a peak of vocal activity around September in the three acoustic monitoring stations (Figure 2, see Supplemental Fig. S3 for mean percentage of calls detected during each month).

Acoustic Monitoring Protocol

The CV of the DVAR of Chaco Chachalaca greatly decreased with the number of monitoring days (Figure 3). A similar decreasing pattern was found at two of the three acoustic monitoring stations, while at the third station, the decreasing pattern showed a different curve (Station A, Figure 3). Overall, we estimated that a minimum number of nine monitoring days were needed to obtain a reliable DVAR (CV<20%), although the CV could decrease by as much as 10% when recording for 15 consecutive days (Figure 3).

Discussion

In this study, we validated for first time passive acoustic monitoring coupled with automated signal recognition software as a useful tool to monitor the vocal behavior and presence of a cracid, the Chaco Chachalaca. The cluster analysis function of Kaleidoscope and the method employed in that study (manually reviewing only the clusters with a high probability of containing a vocalization of Chaco Chachalaca) allowed us to (1) detect the daily presence of the species on 99.7% of the monitored days, (2) detect up to 78% of the calls uttered by the species, and (3) reduce up to 82% the number of candidate sounds to be reviewed. The recognizer employed was able to detect 77.6% of the calls within a recording, which is fully in agreement with four previous studies that monitored seven bird species in the study area applying the same approach (recall rates ranged between 71 and 85%, Pérez-Granados et al., 2021; Pérez-Granados & Schuchmann, 2020a, 2020b, 2021). Those calls detected by the observer but not by Kaleidoscope were likely calls of the Chaco Chachalaca uttered at far distances of the recordings, based on low signal intensity of some of the calls detected in the validation dataset (pers. obs). The spectrograms of some of these calls were very weak, and therefore, they could not have been identified as candidate sounds by Kaleidoscope or may have distorted the estimation of the DCTs made by Kaleidoscope; therefore, these calls could have been undetected or classified within the category "other sounds." The precision of the recognizer (80%) was similar to that obtained in a previous study using the same approach for monitoring the White-Tipped Dove (87%, *Leptotila verreauxi*, Pérez-Granados & Schuchmann, 2020b) but much higher than the estimation obtained for two potoos (*Nictibius* spp.) (9–29%, Pérez-Granados & Schuchmann, 2020a). A low precision value would have had no impact on our results, since every candidate sound of the category "Target species" was verified, but it could preclude the use of this technique in future studies due to the large work effort required to check every candidate sound. It is likely that the high vocal activity, very characteristic call, and long call duration of Chaco Chachalaca (Figure 1) may have allowed Kaleidoscope to create specific clusters containing mostly vocalizations of the target species, thus explaining the high precision found in the study.

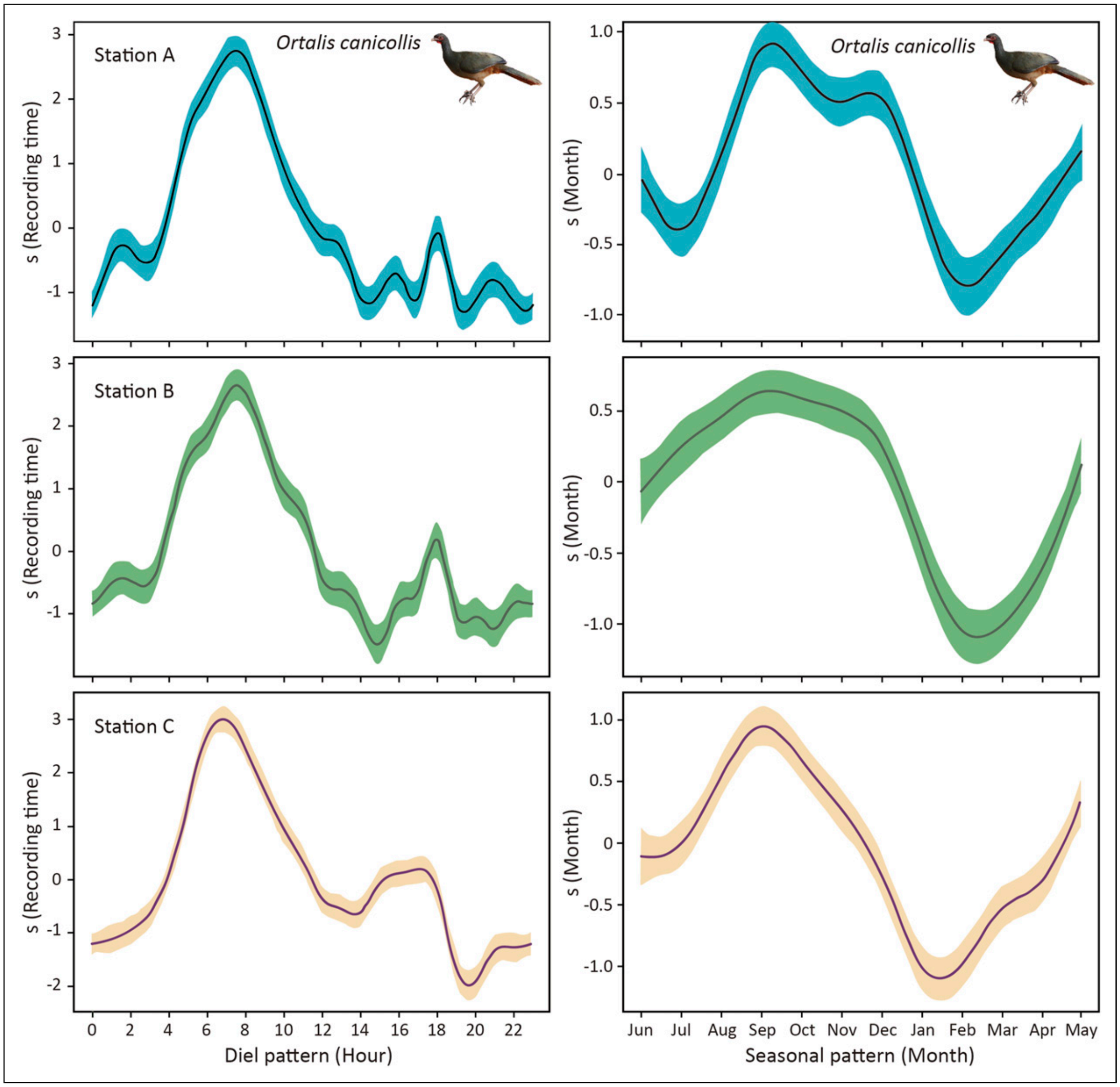

Figure 2. Effects of recording time and month on the calling activity of the Chaco Chachalaca. Estimates of the negative binomial GAM model for each variable are plotted in different colors for the three acoustic monitoring stations. Calling activity was monitored using autonomous recording units from June 8, 2015 to May 31, 2016 at three acoustic monitoring stations. Hours are expressed in winter local time (UTC →4). Colored areas represent associated 95% confidence intervals. Total number and mean percentage of calls detected per recording time and month at each station can be found as Supplemental Material.

Most of the sounds misclassified within the category "Target species" were calls of birds that sang on the same frequency as Chaco Chachalaca, such as the Little Nightjar (*Setopagis parvula*), the White-Tipped Dove and the Undulated Tinamou (*Crypturellus undulatus*). However, there were several vocalizations of the Menwig Frog (*Physalaemus albonotatus*). Although the vocalization of the Menwig Frog is quite different from that uttered by Chaco Chachalaca, the dusk chorus created by that frog (and some others) during the wet season created an almost continuous sound that fell within the signal parameters introduced in Kaleidoscope. The creation of a more advanced classifier or the employment of more sophisticated techniques (i.e., machine learning or convolutional neural networks, Lebien et al., 2020) may be useful in future studies aiming to reduce the number of sounds misclassified.

The study of the activity patterns of cracids is important to understand their biology and contribute to their conservation and management strategies (Baldo & Mennill, 2011; Nunes, 2015; Lavariega et al., 2019). In this study, we identified the hours and months with higher vocal activity of Chaco Chachalaca that will be useful to save efforts of future

Table 1. Summary table of a negative binomial GAM model performed to test the effects of recording hour and month on the calling activity of Chaco Chachalaca in the Brazilian Pantanal. Recording hour and month were modeled applying an independent smoothed function for each site monitored, and the cyclic predictor recording hour was modeled using a cyclic cubic regression spline. Vocal activity was registered using autonomous recording units from June 8, 2015 to May 31, 2016 at three acoustic monitoring stations. Edf (Effective degrees of freedom) shows the degree of curvature of the relationship. A value of 1 for Edf suggests a linear relationship. Values larger than one denote a more complex relationship between the response variable and the predicting one. Ref.df are the reference degrees of freedom used in computing test statistic and the *p*-values.

Parametric Coefficients	Estimate	Standard Error	Z	P
Intercept	0.554	0.032	17.310	<0.001
Station B	−0.261	0.046	−5.641	<0.001
Station C	−0.108	0.045	−2.387	0.017
Smooth terms	**Edf**	**Ref. df**	**X^2**	**P**
s(Recording time):Station A	18.69	22.00	1592.7	<0.001
s(Recording time):Station B	18.42	22.00	1400.7	<0.001
s(Recording time):Station C	16.24	22.00	1901.4	<0.001
s(Month):Station A	8.17	8.81	237.3	<0.001
s(Month):Station B	6.99	8.07	274.9	<0.001
s(Month):Station C	7.83	8.65	355.0	<0.001

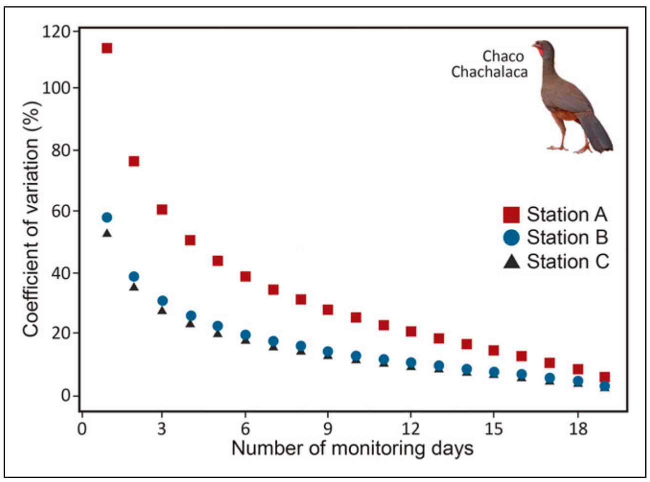

Figure 3. Coefficient of variation (%) of the daily vocal activity rate of Chaco Chachalaca as a function of monitoring days. Vocal activity was monitored using autonomous recording units during the last 20 days of the month of September 2015 in the Brazilian Pantanal at three acoustic monitoring stations. The coefficient of variation of the vocal activity at each acoustic monitoring station is represented by a different symbol.

monitoring programs aiming to study the species. The maximum vocal activity of the species was detected during the first hours after sunrise, which was in agreement with a previous description of the vocal behavior of the species (del Hoyo & Kirwan, 2020). The diel variation in calling activity described for the Great Curassow (*Crax rubra*) in Costa Rica, also monitored using passive acoustic monitoring, showed a very similar unimodal pattern concentrated at sunrise (Baldo & Mennill, 2011). However, while the Chaco Chachalaca was detected vocalizing at any recording hour, including at night, the Great Curassow was not detected between 1700 and 0100 (Baldo & Mennill, 2011). These contradictory results suggest the existence of species-specific differences in diel patterns of vocal activity among cracids. The nocturnal vocal activity of Chaco Chachalaca contributes to the scarce knowledge currently available about the nocturnal vocal activity of diurnal birds (review by La, 2012); however, this type of research has increased in recent years due to the development of autonomous sound recorders (e.g., Celis–Murillo et al., 2016; Foote et al., 2018; Pérez–Granados & Schuchman, 2021).

Our results are in disagreement with previous studies employing video cameras for monitoring daily activity in other cracids, including Chachalacas, which found bimodal patterns in diurnal activity with peaks at sunrise and sunset and no nocturnal sightings (Srbek–Araujo et al., 2012; Lafleur et al., 2014; Lavariega et al., 2019; Senič, 2020). Further research should evaluate whether the nocturnal vocalizations and the unimodal pattern of vocal activity of the Chaco Chachalaca is a rare behavior among cracids or whether it is related to the employment of autonomous sound recorders for monitoring daily activity. It is likely that Chaco Chachalaca may have vocalized while roosting in trees (Caziani & Protomastro, 1994; authors pers. obs.), and therefore, a bird roosting in a tree could have been detected using sound recorders but would have been undetected when using video cameras. Future studies simultaneously monitoring the activity pattern of the same species using wildlife cameras and passive acoustic monitoring may help to unravel this question.

Bird vocal activity has an important function in territory establishment and mate attraction (Catchpole & Slater, 2008). Therefore, the study of seasonal variation in bird vocal behavior might be useful and provide insight into the ecology of monitored species (e.g., Lampe & Espmark, 1987; Amrhein et al., 2002; Polak, 2005; 2006; Catchpole & Slater, 2008). This assumption also seems to be valid for cracids, since in a prior study using passive acoustic monitoring and a cracid as a study model, Baldo and Mennill (2011) linked seasonal changes in calling activity with the breeding behavior of the Great Curassow. According to seasonal changes in the vocal behavior of Chaco Chachalaca, we propose that the breeding season of the species in the Brazilian Pantanal occurs from August onwards, when the first rains usually occur (Junk et al., 2006; de Deus et al., 2020). The proposed starting period of the breeding season agrees with the starting date published for neighboring populations of Bolivia (August, del Hoyo & Kirwan, 2020) and with the nesting period for most bird species in the Brazilian Pantanal (August–November, Bouton et al., 2005; Pinho & Marini, 2014). There is only one published case of an adult Chaco Chachalaca feeding a well-grown young in January in Brazil (del Hoyo & Kirwan, 2020), which corroborates our findings on the reproduction period of the species in the Brazilian Pantanal. We are aware that our results are based on a reduced number of sites and that the described annual pattern of vocal activity may differ among years according to variable rainfall regime. Therefore, further research is needed before any generalization could be made about the seasonality of vocal activity of the species. Future studies seeking to analyze the vocal behavior of the species should attempt to include information about the number of invididuals around recorders, breeding status of vocalizing birds or impact of weather conditions on Chaco Chachalacas' vocal activity as well as about the climate impact on the probability of detecting the species through passive acoustic monitoring.

Previous studies have suggested that vocalization counts and passive acoustic monitoring may be useful tools for monitoring cracid abundance (Jiménez et al., 2003; Baldo & Mennill, 2011). However, a low-error DVAR might be needed to monitor population changes in the species over time (Buxton et al., 2013). According to our results, future studies aiming to monitor changes in the abundance of the Chaco Chachalaca using passive acoustic monitoring should leave the recorders in the field for a minimum number of nine days to obtain a reliable DVAR. Although vocal activity greatly differs among bird species, the nine required recording days are in agreement with the estimates previously published in the two studies that assessed this topic (range of 8–9 days for three bird species, Pérez-Granados et al., 2019b; Pérez-Granados & Schuchmann, 2020c). However, the first step of any passive acoustic program aiming to monitor changes on Chaco Chachalaca abundance using the DVAR should be to validate the relationship between DVAR and Chaco Chachalaca density around sound recorders. Secondly, it would be desirable to estimate whether or not vocal activity and detectability vary over time and space to provide more robust acoustic monitoring recommendations. The development of effective and standardized monitoring protocols using passive acoustic monitoring is desirable and saves costs related to data and device acquisition, saves data analysis time and can be used to base findings on low-error estimates. However, to our knowledge, the development of species-specific or generalized monitoring protocols using this technique has been very little studied (but see Hagens et al., 2018; Pérez–Granados et al., 2018). Considering only the hours (0700 and 0800) and the month with higher vocal activity (September), following our recording schedule (15 min per hour), we were able to detect the species' presence on 86 of the 90 monitoring days (95.6%, all stations pooled), which suggests that there is no need to record 24 h per day if the purpose of the study is to detect the species' presence. The probability of detecting Chaco Chachalaca was reduced to 90% (81 of the 90 days) and 85.6% (77 of the 90 days) when recording only at 0700 and at 0800, respectively.

We would like to clarify that the described protocol (sampling dates and number of days that the recorders need to be deployed in the field) should be used just as a starting point for future studies aiming to monitor the Chaco Chachalaca. Nonetheless, further research is needed and even the protocol may need to be adjusted in other regions due to variation found among sites. The described approach may be helpful as a framework from which researchers may develop their own species-specific protocols for future studies and with different species. In such cases, researchers should try to include a measurement of the effective detection radius (EDR) of the recorder for the target species to correct for the sampling radius of the recorder employed (Buckland et al., 2015; Lambert & McDonald, 2014; Van Wilgenburg et al., 2017). The EDR may differ among habitats, species or recorder employed (Rempel et al., 2013; Metcalf et al., 2020), among others, but once the area surveyed by the recorder is known may facilitate researchers to estimate bird density or estimate population changes from sound recordings (reviewed by Pérez–Granados & Traba, 2021).

Implications for Conservation

Our study has proven, for the first time, the utility of passive acoustic monitoring coupled with automated signal recognition software to detect the presence and study the vocal behavior of a cracid, Chaco Chachalaca. We also provide the most effective sampling periods for monitoring the species, which might be useful for traditional or passive acoustic surveys, and an estimate of the number of days to record a reliable detected vocal activity rate of the species, which might be used for monitoring population abundance changes over time. The use of passive acoustic monitoring for detecting wildlife presence or estimating population trends over time might be especially well suited for monitoring the environmental status of the Pantanal wetland, which is under threat (e.g., Tomas et al., 2019; da Cruz et al., 2021). Indeed, this tool might be especially useful for performing continuous surveys in inundated areas, as we did in the present study, since wildlife monitoring during this period might be an extra challengue to tropical bioacoustic surveys. We hope that our research may guide future studies with the species and encourage researchers to evaluate the use of this technique as a complementary tool to field studies for monitoring other cracids. Passive acoustic monitoring might be particularly useful for monitoring this threatened family (Jiménez et al., 2003) due to the difficulties in monitoring their natural behavior during observational field surveys, since most of them are reluctant to human presence (Martónez–Morales, 1999; Brooks & Strahl, 2000). The use of this noninvasive technique would be useful for detecting the presence and monitoring critically endangered cracids, such as the Trinidad Piping-Guan (*Pipile*, BirdLife International, 2018a) or the Blue-bellied Curassow (*Crax alberti*, BirdLife International, 2018b).

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