DIEL AND SEASONAL PATTERNS OF MARKHAM'S STORM PETREL *HYDROBATES MARKHAMI* IN THE ATACAMA DESERT, CHILE

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ABSTRACT

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Markham's Storm Petrel *Hydrobates markhami* is endemic to the Humboldt Current, breeding inland in Chile and Peru. Its nesting habitat in Atacama Desert saltpeter deposits overlaps with light pollution, roadways, and other anthropogenic disturbances—factors that may impact the species' populations. Owing to its remote nesting locations and nocturnal behavior, finding and monitoring its colonies is challenging. In fact, the first colonies were discovered only recently. In this study, we assessed whether passive acoustic monitoring of this species detects the same activity patterns as active nest monitoring. Acoustic monitors were placed at eight sites within colonies at Caleta Buena (Tarapacá Region) and Pampa Chaca (Arica Region), both located in the Atacama Desert, Chile. Acoustic data were processed with a trained Convolutional Neural Network detection model and analyzed to investigate diel and seasonal patterns. We then compared the call rates in areas with different burrow densities to assess this approach against active nest monitoring. We found that the mean call rate for each site was correlated with estimated nest densities. In both colonies, the seasonal pattern of vocal activity was similar to that reported in the literature based on active monitoring. This study also provides the first description of the species' diel activity: birds of Caleta Buena became active between 102.9 ± 49.6 and 344.6 ± 47.9 min after sunset, and birds from Pampa Chaca were active between 86. 7 ± 23.0 and 187.2 ± 66.6 min after sunset. We conclude that passive acoustic monitoring may be effective for estimating the relative density of Markham's Storm Petrel, especially in the early breeding season. Future monitoring in known colony areas should deploy recorders for longer periods to clarify breeding seasons and compare across colonies.

Key words: automated recording unit, bioacoustics, Convolutional Neural Network (CNN), ecology, passive acoustic monitoring, storm petrel

INTRODUCTION

Markham's Storm Petrel *Hydrobates markhami* is endemic to the Peru Current, nesting inland of the adjacent coast (Murphy, 1936). While its occurrence at sea has been well studied (Spear & Ainley, 2007, 2008), its breeding biology remains poorly understood. It has been classified as Near Threatened by BirdLife International (BirdLife International, 2019), and as Endangered in Chile (Ministerio del Medio Ambiente, 2019). The species' breeding colonies were only recently discovered, with the species found to nest underground in saltpeter deposits in the deserts of southern Peru and northern Chile (Barros et al., 2019; Gallardo et al., 2023; Jahncke, 1993; Medrano et al., 2024; Torres-Mura & Lemus, 2013). Like all petrels, this species returns from the sea to its colonies only at night (Medrano et al., 2024), a behavior that makes it difficult to study. It is allochronic, with northern colonies breeding mainly during the austral winter and the southern colonies breeding during the austral summer (Barros et al., 2019). The species is threatened by light pollution, military activity, powerlines, and roadways (Barros et al., 2019; Norambuena et al., 2021; Silva et al., 2020). Like other storm petrels, individuals vocalize extensively at night (Barros et al., 2019). Although previous surveys have broadly characterized their seasonal vocal activity (Barros et al., 2019; Medrano et al., 2019), finer-scale details of seasonal variation in activity, and how it changes through the night, remain unknown.

Based on active monitoring through site visits, birds of the Pampa Chaca colony, northern Chile, mark their territory and incubate eggs between April and August, with chick-rearing occurring July to January (Barros et al., 2019; Medrano et al., 2019). Birds breeding in the Caleta Buena colony, northern Chile (also referred to as Pampa Perdiz), mark their territories and incubate eggs between November and January, with chick-rearing occurring between January and April (Barros et al., 2019; Medrano et al., 2019). The Pampa Chaca colony is estimated to contain 24,815 breeding pairs, whereas Caleta Buena holds a population of ~624 breeding pairs (Medrano et al., 2019).

Passive acoustic monitoring is an effective tool for monitoring and assessing the relative density of nocturnal burrowing seabirds that are often vocal at night at their colonies (Oppel et al., 2014), as long as the colonies are small (Dunleavy et al., 2018; see also Arneil et al., 2019). Automated acoustic sensors allow for large-scale data collection without disturbance to the birds. New machine-learning techniques, such as Convolutional Neural Networks (CNNs), allow for better-automated detection of calls without an increase in human effort (Orben et al., 2019), as not every call needs to be identified manually (Mackenzie & Royle, 2005). These models can be trained to search for calls of interest and can then comb through huge datasets and identify calls faster and with comparable accuracy to what a human can accomplish (Incze et al., 2018). These advances allow for long-term monitoring of elusive species in less accessible locations, potentially providing information on presence, phenology, and other behaviors.

Passive acoustics can be used to answer diverse questions, including identifying vocal activity and determining the presence and absence of species of interest (Arneill et al., 2019). This information adds to our understanding of the behavioral ecology, conservation, and management of various species. Furthermore, passive acoustics can be used to estimate relative population size of seabird colonies (i.e., which areas within a population have more birds than others, rather than providing actual count data) (Arneil et al., 2019; Borker et al., 2014; Buxton & Jones, 2012; Dunleavy et al., 2018;).

In this study, we used passive acoustic monitoring to understand the vocal activity of Markham's Storm Petrel at two colonies in Chile. Our objectives were to (1) characterize acoustic behavior over diel and seasonal scales at both colonies and over a multi-year scale at Pampa Chaca, and (2) to compare our findings with those obtained via active nest monitoring. We expected that passive acoustic monitoring would show comparable results to active nest monitoring, while providing undescribed details such as start and end times of diel vocal activity and call rate. We also predicted that call rate would be related to burrow density.

METHODS

Study Area

Caleta Buena (20.104621°S, 70.072068°W) is a breeding colony located in the Tarapacá Region of northern Chile (Medrano et al., 2019). It is an evaporitic pampa within the coastal massif of the Cordillera de la Costa, which in turn is located in the hyperarid core, or absolute desert, of the unvegetated Atacama Desert (Ruhm et al., 2020). According to the Köppen-Geiger classification, it is located in a cold coastal desert zone (BWk), where the average annual temperature is < 18 °C, with high evapotranspiration rates exceeding precipitation (which does not surpass 1 mm per year; Peel et al., 2007). The site has an average altitude is 580 m above sea level (a.s.l.) and is located about 5.5 km from the coast (Medrano et al., 2019).

Pampa Chaca (18.699704°S, 70.234430°W) is an evaporite basin located 22 km south of Arica, in the Arica and Parinacota Region of Chile. It is about 9.3 km from the coast, at 608 m a.s.l. (Barros et al., 2019). According to Medrano et al. (2019), approximately 25,000 Markham's Storm Petrel pairs breed here each year. It is located on the eastern flank of the Cordillera de la Costa, an area covered by diverse sediments produced by erosive processes that give rise to sandy sectors and saline crusts (Hernández et al., 2014). The site lies within absolute desert formation with sparse vegetation (Luebert & Pliscoff, 2016). It also exhibits a cold coastal desert climate (BWk type according to the Köppen-Geiger classification).

Recorder Deployment

We deployed acoustic sensors at six sites in the Caleta Buena colony (also known as Pampa Perdiz) and at two sites in the Pampa Chaca colony (Fig. A1, Appendix 1, available on the website). At Caleta Buena, acoustic data were collected using Song Meter 4 (SM4) sensors (Wildlife Acoustics; Maynard, United States). Acoustic recordings were made in stereo using two built-in omnidirectional microphones. The same sensor settings were used for both channels and were as follows: 22,050 Hz sample rate, 16 dB gain, 26 dB preamp, no high-pass filter; data were saved as .wav files. For the Song Meter recorders, the estimated range of detection of Markham's Storm Petrel vocalizations was 50 to 100 m, based on field experience. The Caleta Buena units recorded data from 29 October 2019 to 08 February 2020, operating from sunset to sunrise on a duty cycle of 1.0 min every 5.0 min. Sunset and sunrise times were calculated for 21.090°S, 69.740°W (Datum: WGS 84). The six sensors at Caleta Buena collected data during a total of 536 survey nights and 1,140.8 survey hours. No file corruption or microphone issues were detected. However, two sensors failed early due to battery depletion, resulting in fewer survey days. The last recording from the Caleta Buena Sensor 06 was on 25 December 2019, and from the Caleta Buena Sensor 05 was on 09 January 2020 (Table A1, Appendix 1).

In Pampa Chaca, acoustic data were collected using AudioMoth (version 1.2.0) recorders housed in waterproof cases, manufactured by Silicon Labs (Hill et al., 2019). AudioMoths have one omnidirectional microphone. The same sensor settings were used for all devices as follows: 48,000 Hz sample rate, 16 dB gain, 26 dB preamp, no high-pass filter; data were saved as .wav files. The Pampa Chaca units began recording on 15 April 2021 and concluded recordings on 24 May 2023 (Table A1, Appendix 1). Sensors recorded from 20h30 to 07h30 each night on a duty cycle of 1.0 min/h. They collected data for a total of 1,508 survey nights and 301 survey hours, with 30 nights missing due to battery depletion.

Burrow Surveys

During sensor deployment at Caleta Buena, we surveyed the site for potential burrows. To identify areas of high, medium, and low nest densities, we conducted informal transects 10 m wide and 100 to 2,640 m long, depending on the terrain. We identified all active nests within the transect area and recorded each nest's distance from the transect line (in m). Nests were defined as containing an adult, chick, egg, or showing signs such as odor and/or tracks at the entrance. We also used endoscopes to confirm nest occupancy (Depstech DS450; Shenzhen, China). We then deployed the six acoustic sensors in areas classified as high, medium, and low density. Low density was classified as 0–3 nests, medium as 14–23 nests, and high as 24–52 nests within 100 m of the recorder. These classifications were created as a rough way to divide densities to allow us to test whether there is a relationship between colony density and vocal activity. Two sensors were placed at sites classified as high density, one at medium density, and one at low density. The final two sensors were placed where there were confirmed nests but no assigned burrow density.

Call Classification and Model Performance

Automated analysis of the acoustic recordings was performed with Conservation Metrics' custom detection and classification software. This analysis was based on a Convolutional Neural Network (CNN) model, a machine learning technique in which an algorithm is trained to detect a unique combination of spectro-temporal features found in target sounds (i.e., calls from the species of interest; Cichy et al., 2016; Deng et al., 2013; Min et al., 2016; Schmidhuber, 2015). CNNs are effective in bird call recognition and classification, especially when a strong foundation of calls is built (Incze et al., 2018).

For initial detection and creation of training data, we used a past model built for detecting Leach's Storm Petrel *Hydrobates leucorhous*, whose vocalizations share some features of Markham's Storm Petrel, to help find examples for annotation. Markham's Storm Petrel calls are a series of short, pulsed notes with clear gaps. We annotated 15,716 2-s clips as containing Markham's Storm Petrel and 8,564 2-s clips as containing Gray Gull *Leucophaeus modestus*, the other primary species present in the recordings. We included > 200,000 additional annotated sound clips from other projects around the world with non-target species including barking dogs *Canis familiaris* and talking humans *Homo sapiens*. Artificial sounds such as cars and wind were also present and used as non-target signals. We then used these annotated clips to create a new model designed for detecting Markham's Storm Petrel calls, "MASP_multi_v03" (Fig. A2, Appendix 1). Markham's Storm Petrel vocalizations were found to be abundant in the data from these surveys, and metrics of the newly trained model's performance were excellent for presenting unreviewed model predictions. Using three-fold cross-validation, we calculated a mean precision-recall curve and selected a very conservative threshold with the highest recall at > 0.95 precision (confidence threshold = 0.94, precision = 0.957, recall = 0.578, f1 = 0.786; Fig. A3, Appendix 1).

For analysis purposes, we defined the peak vocal period for the Caleta Buena colony as occurring from 07 September 2019 to 15 January 2020, 180 to 360 min after local sunset. For the Pampa Chaca colony, the peak occurred from 07 April to 07 September in 2021, 2022, and 2023, 120 to 300 min after local sunset. We defined these peak vocal activity periods based on visual inspection of binned call rates across the diel and seasonal scales using data aggregated across all sites. We plotted the average call rate and observed that most vocal activity occurred within consistent time windows. Peak periods were identified by determining when the majority of vocalizations occurred at each colony.

Statistical Analysis

We used a Generalized Linear Mixed Model to investigate whether the qualitative burrow density classes at Caleta Buena were associated with different call rates. We fit daily call counts as the response variable with qualitative burrow density (low, medium, high) as a fixed effect, and site as a random intercept. We used an offset variable representing the count of 1-min recordings for each date during the filtered "peak period." The model used a negative binomial response distribution to account for overdispersion, and we fit models with the "glmmTMB" package in R 4.4.1 (Brooks et al., 2017; R Core Team, 2024). "Site" was included as a random effect to account for non-independence among observations from the same location. Although there were few sites ($n = 4$), this approach is valid when the primary objective is to model dependencies in the data rather than to estimate the variance component (Gelman & Hill, 2007; Harrison et al., 2018). We used the "emmeans" package to perform post-hoc comparisons with Tukey adjustments for multiple comparisons (Lenth, 2024).

RESULTS

Detection of Markham's Storm Petrel

Markham's Storm Petrel calls, totaling 244,544, were detected and confirmed at all eight survey sites. At Caleta Buena and Pampa Chaca, we detected 226,763 and 17,781 calls, respectively. Sites within the same colony showed similar patterns to one another on multiple scales.

Diel Patterns

At Caleta Buena, vocal activity began on average 102.9 ± 49.6 min after sunset, with the earliest start time occurring 0.45 min after sunset (Fig. 1). Vocal activity concluded 305.4 ± 51.9 min before sunrise, with the latest stop time occurring 168.2 min before sunrise (Fig. 2). All recorders at Caleta Buena consistently showed a maximum peak in activity at ~210 min after local sunset (Fig. 3). Caleta Buena 02 and Caleta Buena 05 had the highest mean call rates of 14.5 ± 7.4 and 12.1 ± 6.7 calls/min, respectively (Table A2, Appendix 1). Caleta Buena 01 had the lowest mean call rate of 4.6 ± 3.8 calls/min (Table A2, Appendix 1). All Caleta Buena sites had vocalizations detected on every survey night during the primary nesting season (Table A2, Appendix 1).

At Pampa Chaca, vocal activity began 86.7 ± 23.0 min after sunset, with the earliest start time occurring 60.9 minutes after sunset (Fig. 1). Vocal activity concluded 579.8 ± 65.2 min before sunrise, with the latest stop time occurring 30.3 min before sunrise (Fig. 2). Both Pampa Chaca 01 and Pampa Chaca 02 showed a nightly peak at ~150 min after sunset (Fig. 3). Both sites also had similar mean call rates each year. At Pampa Chaca 01, mean call rates (calls/min) were 9.0 ± 5.7 in 2021, 3.1 ± 3.6 in 2022, and 3.2 ± 3.4 in 2023. At Pampa Chaca 02, they were 7.3 ± 5.5, 3.8 ± 3.7, and 1.7 ± 2.1 for the same years, respectively (Table A2, Appendix 1). Pampa Chaca peaked earlier in the night than Caleta Buena and had a daily window of vocalizations smaller than that of Caleta Buena. Pampa Chaca did not have a significantly earlier start time for vocalizations but did reach peak activity sooner (Fig. 3). Pampa Chaca sites detected vocalizations on 57%–86% of the nights during the breeding season each year (Table A2, Appendix 1).

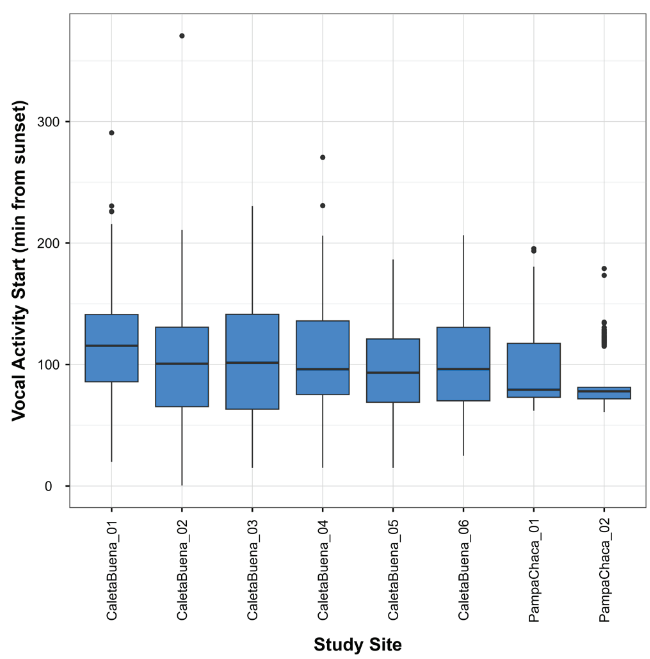

Fig. 1. Average daily start time of Markham's Storm Petrel *Hydrobates markhami* vocal activity (in minutes after sunset) for all study sites in the Caleta Buena and Pampa Chaca colonies, Chile.

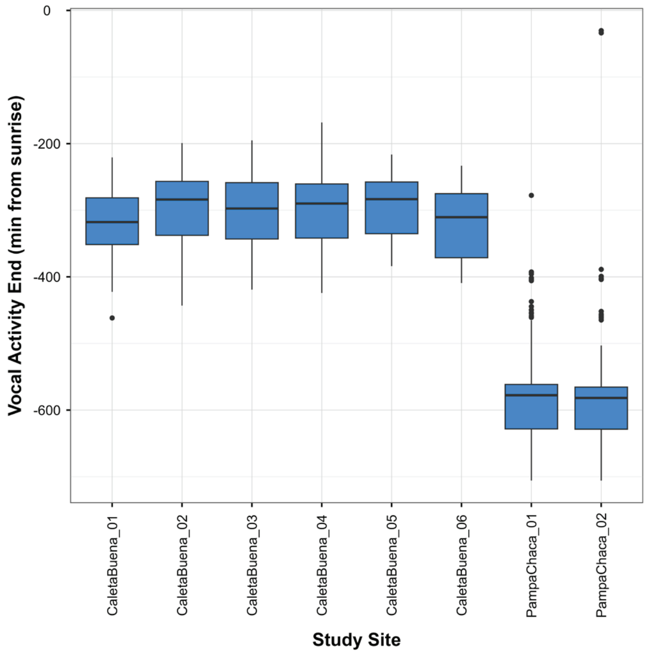

Fig. 2. Average daily end time of Markham's Storm Petrel *Hydrobates markhami* vocal activity for all study sites in Caleta Buena and Pampa Chaca, Chile. Negative values indicate time before local sunrise.

Seasonal Patterns

At Caleta Buena, vocal activity was detected between 07 September 2019 and 15 January 2020, largely within what is thought to be the incubation stage of Markham's Storm Petrels at this colony (Fig. 4). Activity had already begun when the sensors were first deployed and tapered off through the end of January. There was an increase in activity at the beginning of November and again in late December, along with a large decrease in activity in late November.

At Pampa Chaca, vocal activity was detected between 07 April and 07 September each year (2021, 2022, and 2023; Fig. 4). Vocal activity was comparably high throughout the season in 2021 but was lower in 2022 and 2023 (Figs. 4, 5). As with Caleta Buena, vocal activity was primarily detected during the incubation stage at this colony.

Does Call Rate Correlate with Site Density?

Qualitative burrow density was an valuable predictor of call rate at Caleta Buena. Low density sites had 5.0 (4.1–5.8 confidence interval [CI]; 0.46 standard error [SE]) calls/min, medium density sites had 10.5 (9.1–12.2 CI; 0.73 SE) calls/min, and high-density sites had 13.3 (12.1–14.5 CI; 0.62 SE) calls/min. Differences in call rates were significant between all three burrow density categories (Tukey z-ratio: 2.94-9.98; $P < 0.01$). The two sites (Caleta Buena 04 & Caleta Buena 06) where density was not measured had call rates most similar to medium and low-density rates (Fig. 6).

DISCUSSION

These analyses offer insight into the vocal patterns of Markham's Storm Petrels, as observed through passive acoustic monitoring. We characterized the timing of vocal activity on diel and seasonal scales and provided evidence that burrow density is related to call rate at a relative scale. As with many recent studies, we found passive acoustic monitoring to be an effective technique for monitoring presence and activity patterns of these nocturnal seabirds.

When sensors were deployed in late October at Caleta Buena, vocal activity had already begun but continued into November and December (see also Barros et al., 2019). More recent reports, however, show calling from August to April (Araneda et al., 2023; Red de Observadores de Aves y Vida Silvestre de Chile [ROC], 2024), highlighting the value of continuous monitoring. Our data support the updated breeding timeline. The decline in vocal activity at the end of December is consistent with previous studies, with most activity generally occurring during the incubation stage (Barros et al., 2019; Medrano et al., 2019). However, there was still some vocal activity until mid- to late January, which does align with the expected timing of adults leaving the nest, resulting in a quieter colony. Vocal activity generally occurred 100 to 345 min after sunset, with some variation.

At Pampa Chaca, vocal activity occurred from approximately 85 to 185 min after sunset. Seasonal trends largely match previous literature regarding phenology (Araneda et al., 2023; Barros et al., 2019; Medrano et al., 2019; ROC, 2024). At both colonies, monitoring did not show significant vocal activity after incubation, indicating that passive acoustic monitoring becomes less effective for estimating relative colony size during these stages. Colonies must then be monitored with other approaches such as active monitoring of burrows. This is crucial information if passive acoustic monitoring is to be used to survey other colonies, especially when an environmental assessment is being conducted. Therefore, acoustic monitoring should be combined with other methods like those described by ROC (2024) and Servicio de Evaluación Ambiental (2024).

At all sites, activity shifted as local sunset time changed, except on days where vocal activity began earlier or ended later than average, which may be related to moon phase and/or meteorological conditions (e.g., cloud cover). Conditions affecting moonlight intensity may result in changes in vocal activity patterns as a method of predator avoidance (Watanuki, 1986), but further information is needed to determine whether this is the case for Markham's Storm Petrel.

In our research, we found some differences in call rates between years. However, these findings should be further investigated using a longer-term dataset to determine whether interannual differences in call rates reflect actual changes in colony activity rather than differences in the timing of data collection within the breeding season. We do note that in field surveys, nest occupancy was monitored and did not vary across those years (Medrano et al., 2024). A longer dataset capturing the full breeding season across multiple years, paired with burrow surveys, would be most appropriate to answer this question.

The relationship between the qualitative burrow density categories and relative call rates suggests that, with caveats, there may be a functional relationship between burrow density near a sensor and call rate of Markham's Storm Petrel. Dunleavy et al. (2018) found that for Leach's Storm Petrel and Fork-tailed Storm Petrel *Hydrobates furcatus* in British Columbia, song meters could effectively measure actual density only within a few meters of

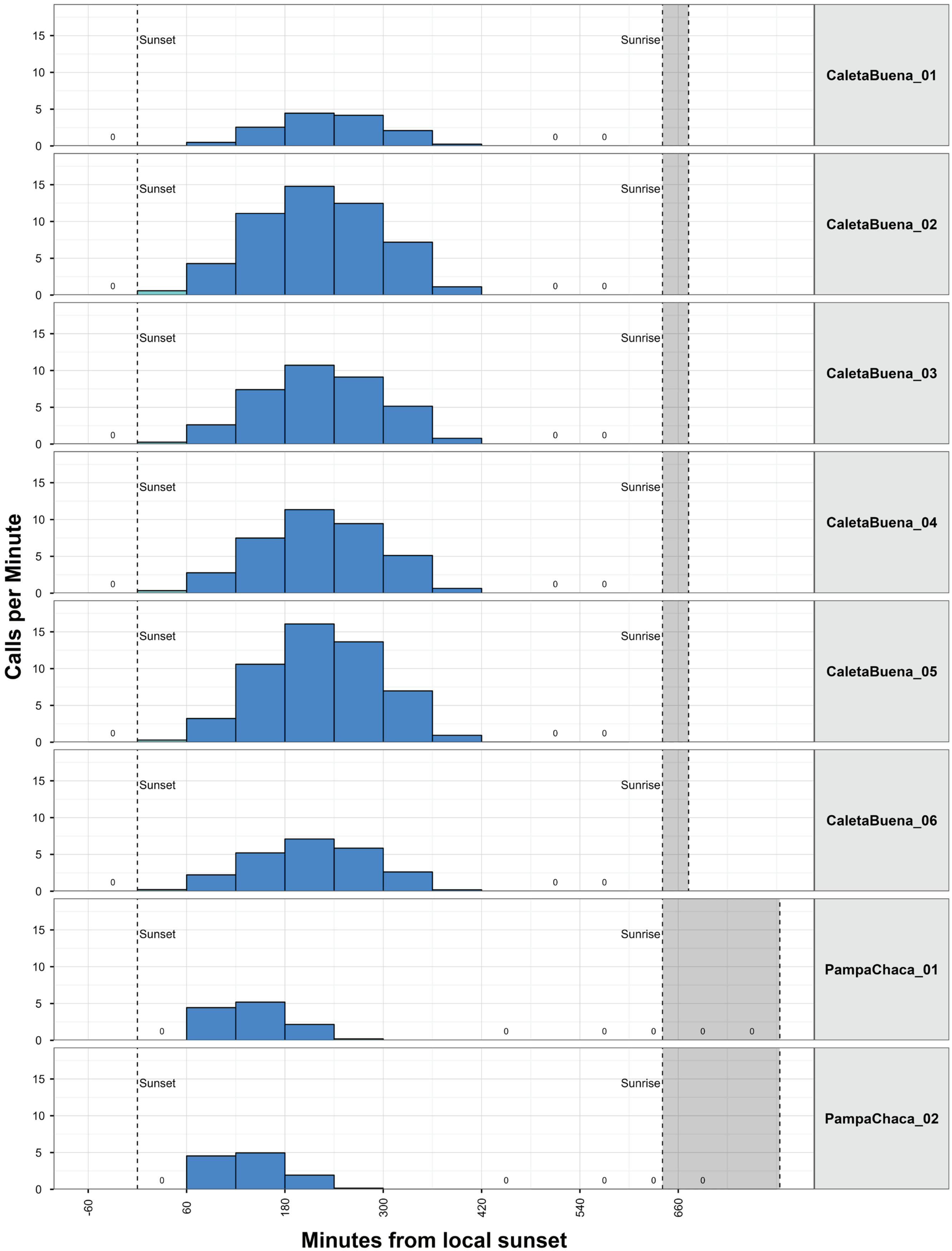

Fig. 3. Markham's Storm Petrel *Hydrobates markhami* diel calling activity for all study sites.

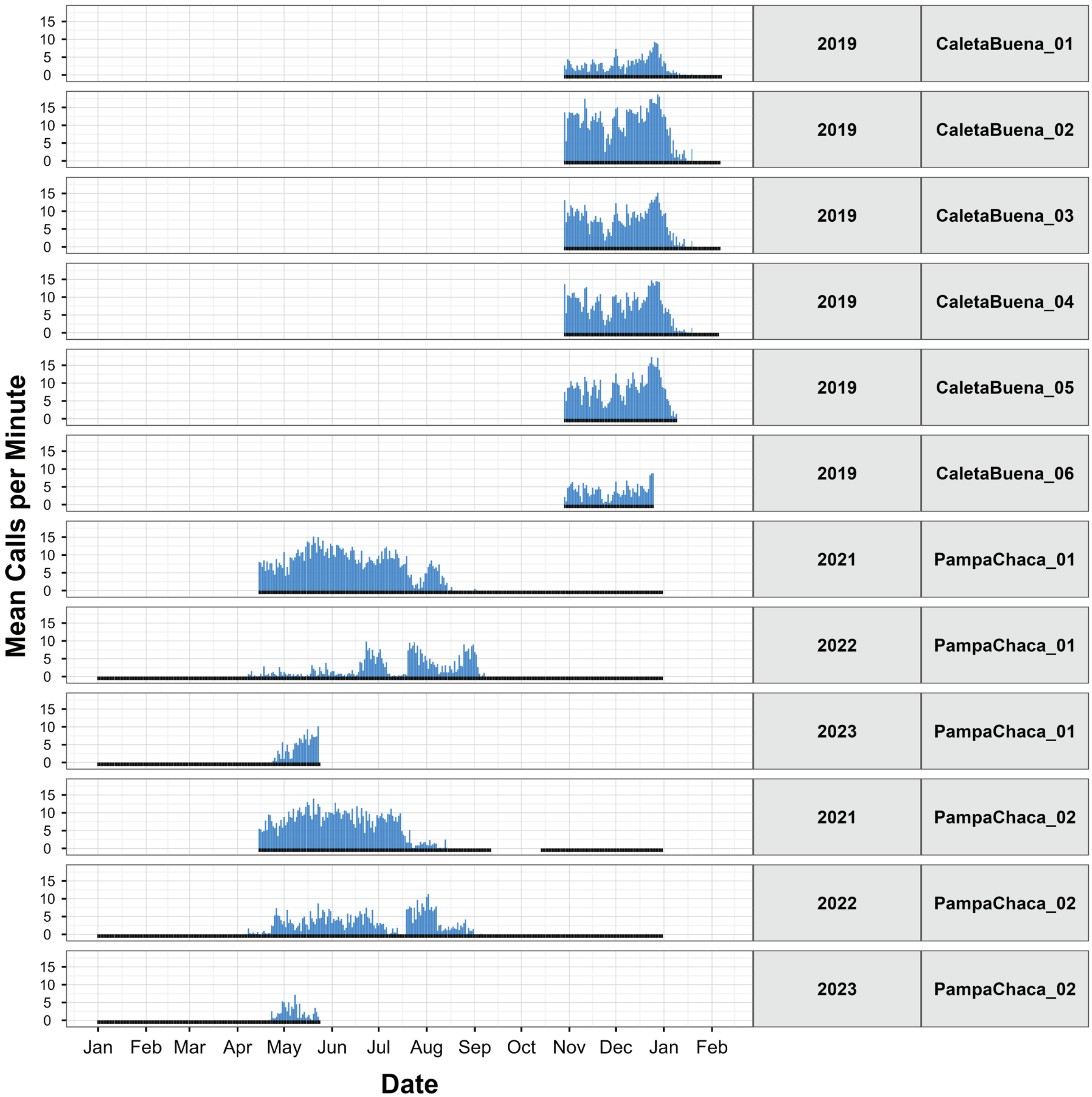

Fig. 4. Seasonal variation in calling activity of Markham's Storm Petrel *Hydrobates markhami* at study sites at the Caleta Buena and Pampa Chaca colonies, Chile. Blue bars indicate the mean nightly call rate during the peak vocalization period (180–360 min after sunset at Caleta Buena; 120–300 min after local sunset at Pampa Chaca). Black line indicates days when recorders were deployed and operational.

the instrument. Future studies of Markham's Storm Petrel should investigate this relationship further by increasing the number of sites, colonies, and years studied, as well as by recording quantitative burrow densities at increasing distances from an instrument. Studies in other species support the potential for this approach. For example, an investigation of the relationship between call rates and burrow density in Wedge-tailed Shearwater *Ardenna pacifica* using concentric circular plots within 10, 20, and 50 m of the instrument found a relationship between vocal activity and occupied burrow density (Smith & Mathieson, 2024). Similarly, vocal activity was found to be an effective proxy for relative density for Forster's Terns *Sterna forsteri* (Borker et al., 2014). In contrast, a study incorporating GPS data found that vocal activity was more closely related to flight activity in and around the colony than to burrow density in the Manx Shearwater *Puffinus puffinus* (Arneill et al., 2019).

Our study complements previous literature describing the phenology of Markham's Storm Petrel at colony sites in the Atacama Desert, and provides important information for planning future colony

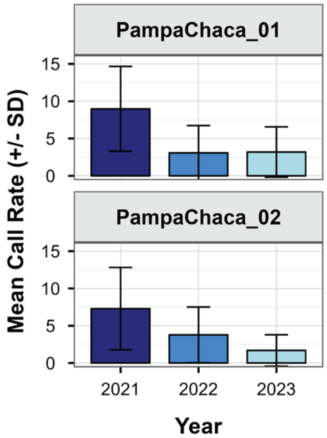

Fig. 5. Mean call rates of Markham's Storm Petrel *Hydrobates markhami* at study sites in the Pampa Chaca colony, Chile, across three study years. Bars are colored by year.

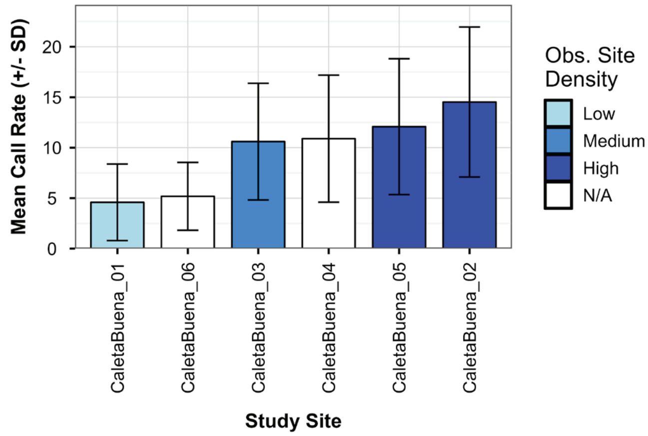

Fig. 6. Mean call rates of Markham's Storm Petrel *Hydrobates markhami* at study sites at Caleta Buena, Chile. Bars are colored according to observed site density.

visits, searching for new colonies, and advising on projects that may impact these birds. Future studies could investigate drivers of vocal activity, such as lunar phase and meteorological conditions, as well as determine the impact of anthropogenic light sources on these birds.

RECOMMENDATIONS

Future surveys at the Caleta Buena colony should begin earlier to capture the entire breeding season and determine when vocal activity begins, peaks, and ends. Researchers should note that breeding timelines differ significantly among colonies. Documenting differences in call rate at different stages of the breeding cycle is also necessary, as such differences are understudied. At Caleta Buena, the period from the beginning of vocal activity to when fledglings are no longer present is seven months. However, at other sites such as the Arica colonies (which include Pampa Chaca), this period is 10 months (Barros et al., 2019). Finally, the role of "floaters" (i.e. adults without breeding burrows; Ainley et al., [2024]) in vocal activity detected by acoustic monitors should be ascertained, as this phenomenon may explain some of the findings of Arneill et al. (2019). A larger number of sensors at the colony and at the Salar Grande colony (another colony observed to have a similar breeding cycle as Caleta Buena) could be useful for comparison. Breaking down calls into types or identifying calls from chicks and juveniles may also aid this effort. It is also necessary to identify what factors may interact with lunar phase to influence vocal activity. Furthermore, analyzing other species such as the Near Threatened Ringed Storm Petrel *Hydrobates hornbyi*, or possible antagonistic species like the Grey Gull or Western Barn Owl *Tyto alba*, may shed light on species interactions in the area.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

AUTHOR CONTRIBUTIONS

MEP: Conceptualization, data analysis, writing—original draft. ABF: Conceptualization, data analysis, writing—review & editing. JS: Conceptualization, data transfer management. GA: Work in field to deploy, recover, and maintain acoustic units, storage of data for Pampa Chaca. BG: Coordination of, and work in field, to deploy, recover, and maintain the acoustic units, and storage of data for Pampa Chaca, writing—editing. PG: Coordination of, and work in field, to deploy, recover, and maintain the acoustic units, and storage of data for Pampa Chaca, writing—editing. RP: Work in field to deploy, recover, and maintain acoustic units for Pampa Chaca. BK: Conceptualization, deployment of acoustic monitors, writing—original draft. FM: Conceptualization, organization of team, writing—original first draft.

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