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Summer calling activity patterns of a bird assemblage in a Valdivian temperate rainforest biodiversity hotspot

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ABSTRACT

Birds generally produce vocalisations in specific daily temporal windows. Describing diel-calling activity patterns along with taxonomic group and guild membership increase the knowledge about potential factors shaping the behaviour of these animals. This information is also highly relevant for the enhancement of monitoring plans for conservation. We performed a passive acoustic monitoring to describe the diel calling activity patterns of a bird assemblage within the Valdivian temperate rainforest, associating the patterns to taxonomic group and diet guild, and also aiming to contribute to the enhancement of ecological monitoring within this biodiversity hotspot. Our results indicate that high richness levels are detected around sunrise and sunset. Also, within the bird assemblage studied, most birds show diurnal vocal activity, among which several were also active during crepuscular periods, and only two species had nocturnal vocal activity. Among diurnal birds with enough number of detections to perform a detailed description of diel calling patterns, our results did not show clear trends considering diet guild or taxonomic group. We expect that this information encourages future research to increase the understanding on the factors influencing vocal activity patterns, as well as population and community trends from this biodiversity hotspot.

Introduction

Animals generally perform their activities in specific daily temporal windows. Based on their diel activity, animals can be classified as diurnal, nocturnal, crepuscular and cathemeral species. Describing these patterns along with taxonomic group, guild membership and/or functional traits increases the knowledge about potential factors shaping the behaviour of animals and may also contribute to the understanding of community structure. Furthermore, this information is needed for the enhancement of monitoring

plans of relevance for conservation policies (Ridout and Linkie 2009; Schwartz et al. 2010; Bu et al. 2016; Ikeda et al. 2016; Caravaggi et al. 2018).

Most studies of calling activity in birds have focused on the hours comprising dawn, daytime and dusk; nevertheless, calling may not be restricted strictly to some of these periods. For instance, diurnal species may also vocalise at night (Marler and Slabbekoorn 2004; La 2012; Kułaga and Budka 2020) and nocturnal raptor species may show peaks of activity soon after sunset (e.g. Clément et al. 2021). Thus, 24-h sampling protocols are appropriate to obtain more precise descriptions of the calling activity patterns of bird communities. Recent improvements in passive acoustic monitoring (PAM) using autonomous recording units (ARUs) allow to obtain information on a daily basis at a relatively low cost and without interfering with the normal activity of animals (Darras et al. 2018; Kułaga et al. 2019). Studies reporting complete 24-h diel calling activity patterns of birds are increasing (Jahn et al. 2017; Pérez-Granados and Schuchmann 2020; Morales et al. 2022). Examples include the Chaco Chachalaca (*Ortalis canicollis*) that showed an unimodal calling pattern (Pérez-Granados and Schuchmann 2021) and the Band-tailed Nighthawk (*Nyctiprogne leucopyga*) that showed a prominent activity peak after sunset but a secondary peak before sunrise (Pérez-Granados and Schuchmann 2022).

The calling activity patterns of birds are influenced by intra- and interspecific interactions, such as competition for the acoustic space or predation risk, and environmental conditions. For instance, calling at dawn may be associated with an enhanced probability of acquiring mates and establishing territories, which is expected to be reinforced by a diminished foraging success at a time when low light levels impair food detection (Staicer et al. 1996; Gil and Llusia 2020). Nevertheless, visual capabilities vary among taxa, implying differential effects among species of light levels on food detection (Garamszegi et al. 2002). In addition, variations in type of preferred food, availability and profitability may also affect foraging activity patterns (e.g. Reyes-Arriagada et al. 2015). Therefore, besides social interactions, calling patterns can also relate to types of preferred food and visual capabilities (Staicer et al. 1996; Gil and Llusia 2020). However, the importance of these factors in explaining calling patterns varies among taxonomic groups, as has been reported for passerine and non-passerine birds (Berg et al. 2006). As such, it is likely that birds that belong to the same diet guild and/or that have taxonomic affinity show similar calling activity patterns (Ehnes et al. 2018; Bolaños-Sittler et al. 2021).

Knowledge of bird activity patterns is highly relevant for the conservation of native forest ecosystems, as birds have functional roles such as seed dispersers, pollinators or controllers of the abundance of other species (Clout and Hay 1989; Armesto et al. 1996; Bereczki et al. 2014). In addition, native forest ecosystems are inhabited by endemic birds having specific habitat requirements, a condition that renders them appropriate indicators of habitat degradation and fragmentation (Reid et al. 2002; Amico et al. 2008). The description of calling activity patterns contributes to the design and implementation of efficient ecological monitoring programmes, which are particularly needed in areas of high biodiversity value (Caravaggi et al. 2018; Ehnes et al. 2018; Kułaga et al. 2019; Sugai et al. 2019). Such recordings are instrumental for assessments of the effects of ongoing global change at species, community and ecosystem levels (Krause and Farina 2016).

The Valdivian temperate rainforest is an important component of the Chilean biodiversity hotspot, which is a globally recognised area for conservation due to the high level

of endemism and threatened status of its native species (Myers et al. 2000). In general, its acoustic environments are relatively simple when compared to tropical forests: most biophonies are produced by birds and amphibians, and geophonies are mainly produced by rain and winds (Penna and Veloso 1990; Bartheld et al. 2011; Moreno-Gómez et al. 2013, 2019). About 44 bird species inhabit this forest, among which 13 are endemic (Reid et al. 2002; Díaz 2005). Vocally conspicuous birds that are specialist endemic species threatened by habitat fragmentation include Chucao tapaculo (*Scelorchilus rubecula*), Black-throated Huet-huet (*Pteroptochos tarnii*), and Thorn-tailed Rayadito (*Aphrastura spinicauda*) (Reid et al. 2002; Willson 2004; Díaz 2005; Moreno et al. 2014). Species involved in plant-animal mutualistic interactions such as pollination and seed dispersal include Green-backed Firecrown (*Sephanoides sephaniodes*), White-crested Elaenia (*Elaenia albiceps*) and Austral Thrush (*Turdus falcklandii*) (Armesto et al. 1996). Among raptors, the owls Austral Pygmy-owl (*Glaucidium nana*) and Rufous-legged Owl (*Strix rufipes*) predate over different animal taxa including insects, birds and mammals (Jiménez and Jaksic 1993, Martínez and Jaksic 1996, 1997).

In this study, our aims were to describe the summer diel calling activity patterns of a bird assemblage within the Valdivian temperate rainforest, and to relate these patterns to taxonomic group and diet guild. We expect that this information will also contribute to the enhancement of ecological monitoring within this biodiversity hotspot.

Materials and methods

Study site and acoustic monitoring

The study was performed in Parque Oncol, a private reserve located in southern Chile, throughout three consecutive summer months starting in January 2017, corresponding to the post-breeding season and when birds are still vocally active. We placed four acoustic recorders (two SM1, one SM3 and one SM4 Wildlife Acoustics) at four stations (S1: 39°41'58.16"S, 73°17'41.51"W; S2: 39°42'4.45"S, 73°18'0.65"W; S3: 39°42'17.67"S, 73°18'33.85"W; S4: 39°42'0.26"S, 73°18'25.46"W) during 11 consecutive days every month. Neighbouring recorders were placed at a distance around 550 m. The location of each station was associated to its accessibility within the forest. Each acoustic recorder was placed always in the same station, attached to a tree at 5-m elevation. Acoustic recorders were set to record at a sample rate of 44,100 Hz with a resolution of 16-bit. Other recorder parameters were set to default values. Recordings were made for 1 min starting every hour (i.e. 24/7). Due to technical problems with one recorder (S3), the number of recordings obtained was not identical throughout the months sampled, resulting in 1127 for January, 954 for February and 848 for March, yielding a total of 2929 audio files for the analysis (S1: 864, S2: 855, S3: 377 and S4: 833 audio files). Each file was downsampled to 22,050 Hz as a part of a previous study (Moreno-Gómez et al. 2019). Audio-visual analysis was performed using Raven Pro 1.4 (Bioacoustics Research Program 2011). Spectrograms were obtained with a frequency resolution of 43 Hz and used to determine the presence/absence of each species in the acoustic recordings. This analysis was done by JB, an experienced researcher. Calls were classified using a previous sound library made by our team (Bartheld et al. 2011) and also using the online platform https://xeno-canto.

org/. The analyses considered each all vocalisation types produced by species. Because the sunlight hours varied throughout the sampling period, the sunrise and sunset of each recorded day were obtained using the R (R Core Team 2021) library suncalc (Thieurmel and Elmarhraoui 2019). According to the library, sunrise is defined as follows: 'top edge of the sun appears on the horizon', and sunset as: 'sun disappears below the horizon, evening civil twilight starts'. The recording hour of each audio file was expressed as hours after sunrise.

Number of species detected

Call detections were used to obtain coverage-based and sample-size-based rarefaction/ extrapolation species richness curves of each ARU and for each month by using the library 'iNEXT', where the Hill number of order q = 0 was used for estimation using 1000 replications (Hsieh et al. 2022). Variations in the number of species detected by calls during hours and months were evaluated using a zero-inflated generalised linear mixed-effects model with a Poisson family distribution (log link), where the station was included as a random effect to account for data dependence. Model fitting was performed using the library glmmTMB (Brooks et al. 2017) and the significance of the fixed effects was obtained using the library car (Weisberg 2019). In order to exclude extremely rare species, only species with at least three detections were included.

Vocal activity patterns

To classify the main diel activity pattern of each species, the diurnal period was defined as the time interval starting 1 h after sunrise and ending 1 h before sunset; the crepuscular period corresponded to the period encompassing 1 h before and after sunrise, and 1 h before and after sunset; the nocturnal period corresponded to the time occurring between 1 h after sunset and 1 h before sunrise (e.g. Ikeda et al. 2016). During January sunrise and sunset occur around 0630 and 2130, respectively. According to the library suncalc, while nautical twilight starts around 30 min after sunset, astronomical twilight starts around 70 min after sunset. For species having at least 20 detections during the entire monitoring, selection ratios (Manly et al. 2004) were obtained to determine if species were more vocally active during day, night, or crepuscular periods. Selection ratios (Wi) and tests of non-random use were obtained with the library adehabitatHS using the *widesI* function, which assumes no individual identification. Wi > 1 values indicate that species are selectively using a time period and Wi < 1 values indicate that species are avoiding a period (Calenge 2006).

For species having at least 20 detections within a sampled month, the diel call activity pattern was obtained through kernel density estimation using the function *densityPlot* from the library overlap (Ridout and Linkie 2009). Using the library activity (Rowcliffe 2021), overlap values between activity distributions among pairs of species were obtained with the function *ovl4*. Overlapping values were visualised through a heatmap coupled with a dendrogram obtained by hierarchical clustering using the library heatmaply (Galili et al. 2017).

Results

Number of species detected

In total 26 species were detected and accession to their vocalisations is available in the supplementary material S1. Only one species had less than three detections, corresponding to the Magellanic Woodpecker (*Campephilus magellanicus*, Piciformes: Picidae), detected just in one recording during February. Considering species with at least three detections, sample-size-based and coverage-based rarefaction/extrapolation species richness curves depict variations in the number of species detected among sampling stations, ranging from 24 species detected in S1 to 20 species in S2 (both SM1); nevertheless, higher uncertainty was observed in S3 (SM3), which corresponds to the station with less data. Pooling the data from the four recording stations, during January, February and March, the observed species richness was 25, 23 and 21, respectively. For these months, estimated richness was 25.5 (25.0–29.0), 23.0 (23.0–25.1) and 33.5 (21.0–54.3), the estimation for March being the less accurate (Figure 1). Significant differences in the number of detected species occurred among hours ($X^2_{(23)} = 937.529$, $p < 0.001$) and months ($X^2_{(2)} = 292.381$, $p < 0.001$). Higher numbers of species were detected in the hours around dawn and dusk, and the number of species detected during March was lower relative to January and February (Figure 2). The Passeriformes order was the most represented, including 16 species (64%), the Piciformes and Strigiformes orders included two species (8%) each, and the Apodiformes, Columbiformes, Falconiformes, Pelecaniformes and Psittaciformes orders included one species (4%) each. Regarding the diet guilds, the insectivore guild was the most represented, including 14 species (56%), in addition, the remaining species detected were three omnivores (12%), two carnivores (8%), two frugivores (8%), two granivores (8%), one nectarivore (4%) and one carnivore opportunistic (4%).

Vocal activity patterns

The species having the highest number of vocal detections were Chucao Tapaculo (*Scelorchilus rubecula*, Passeriformes: Rhynocriptidae), Green-backed Firecrown (*Sephanoides sephaniodes*, Apodiformes: Trochilidae) and White-crested Elaenia (*Elaenia albiceps*, Passeriformes: Tyrannidae). The total number of detections for species having at least three detections during the entire monitoring interval and the proportion of detections within the time periods crepuscular, diurnal, and nocturnal are depicted in the supplementary material S2. To obtain selection ratios, a minimum of 20 detections during the entire monitoring was needed, a requisite that was fulfilled for 17 species. As shown in Table 1, all of these species showed a significant non-random use of time periods (p-value < 0.05), as Wi > 1 values indicate that species are selectively vocalising within a time period. Species having a carnivore diet and that belong to Strigiformes: Strigidae, i.e. Rufous-legged Owl (*Strix rufipes*) and Austral Pygmy-owl (*Glaucidium nana*), showed crepuscular and nocturnal patterns, although for Austral Pygmy-owl the standard error value implies a non-consistent estimate for the nocturnal period (i.e. Wi – SE < 1). All other species showed consistent diurnal patterns, including species having insectivore, granivore, frugivore, nectarivore and omnivore diets. Among these species, consistent crepuscular patterns occurred for insectivores that belong to Passeriformes
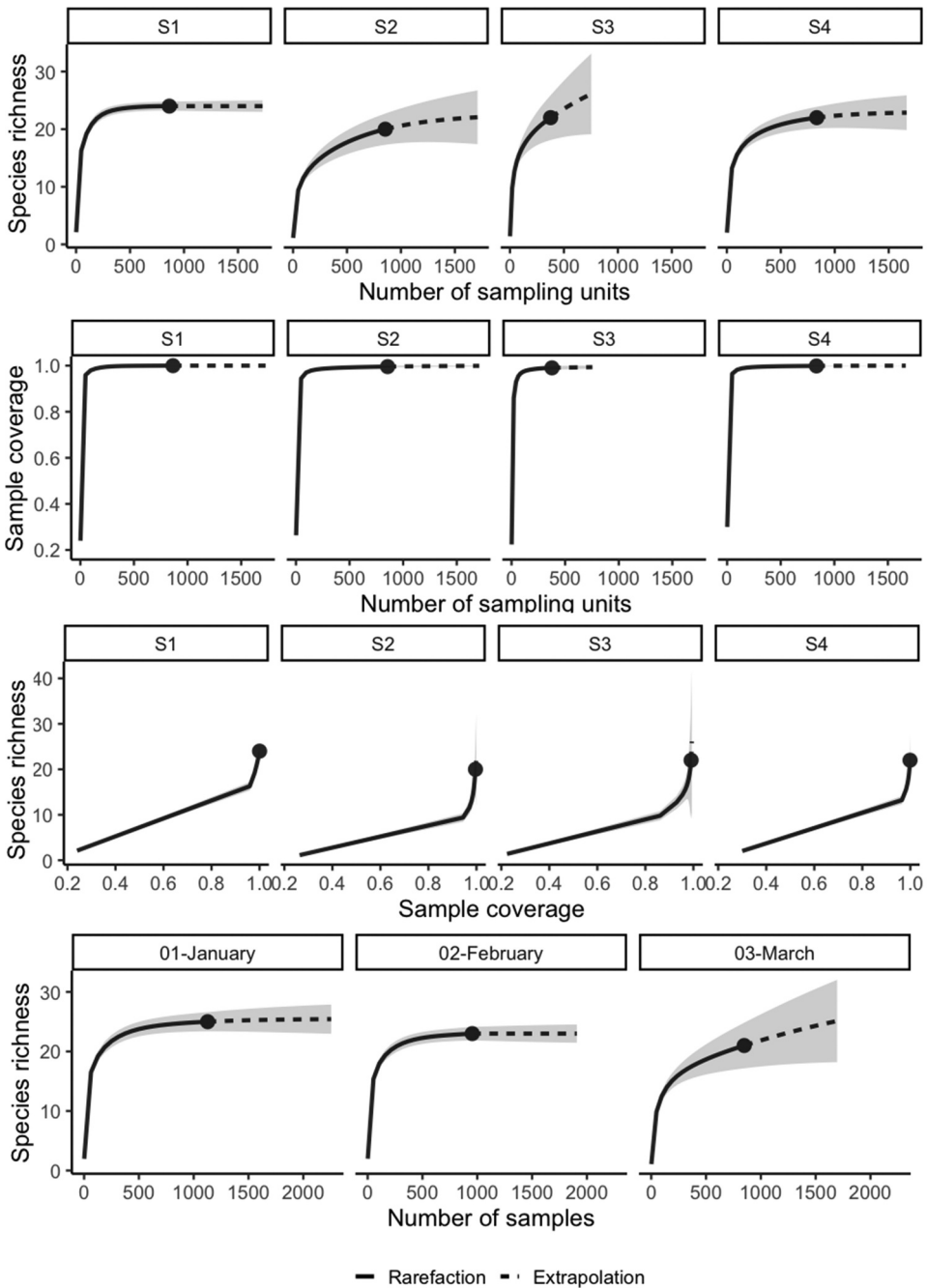
Figure 1. Sample-size-based and coverage-based rarefaction/extrapolation species richness curves for stations and months. Species having at least three detections during the entire monitoring interval were considered for the analyses.

from the families Furnariidae, i.e. Thorn-tailed Rayadito (*Aphrastura spincauda*) and Des Mur's Wiretail (*Sylviorthorhynchus desmursii*) and Rhinocryptidae, i.e. Ochre-flanked Tapaculo (*Eugralla paradoxa*), Black-throated Huet-huet (*Pteroptochos tarnii*) and
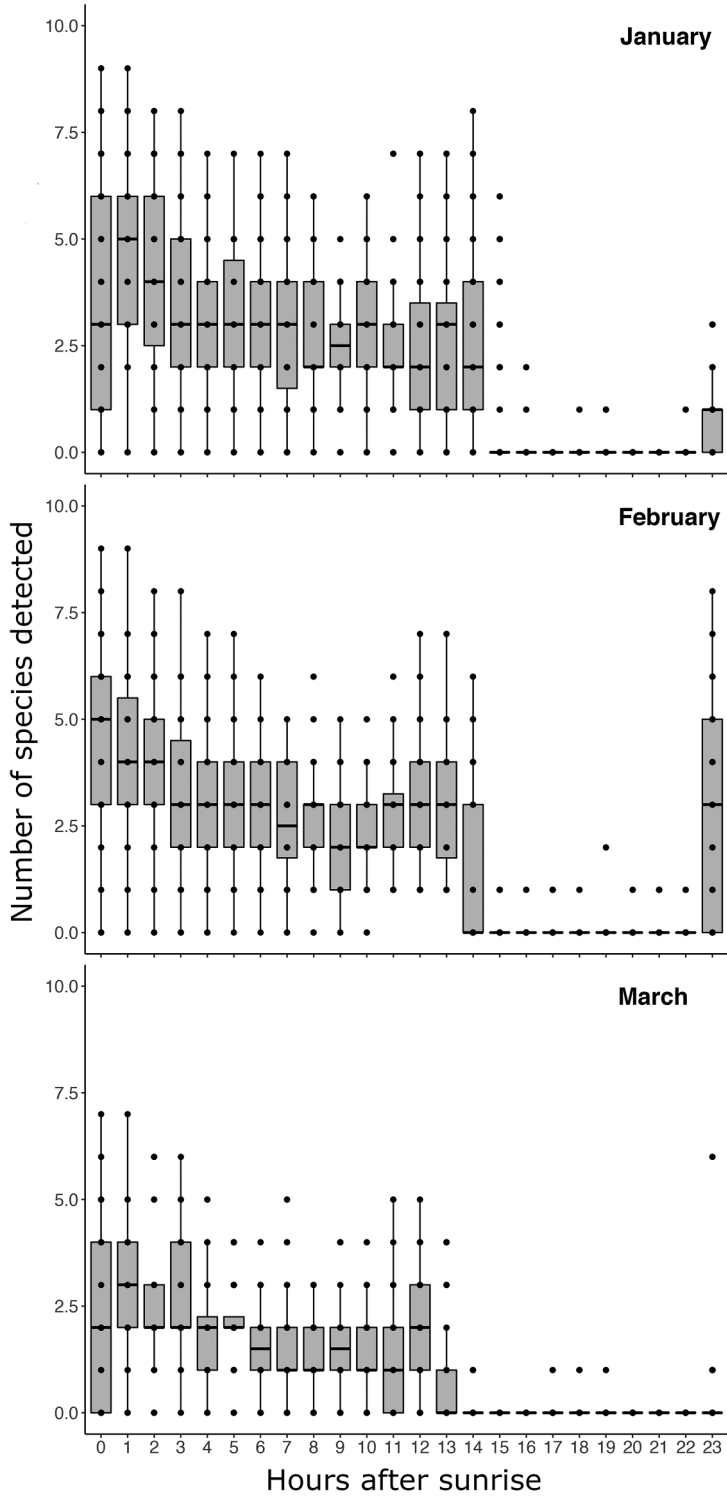
Figure 2. Number of bird species detected by calls hourly during the three months. Species having at least three detections during the entire monitoring interval were considered for the analyses. Median, quartiles and ranges are shown.

Magellanic Tapaculo (*Scytalopus magellanicus*). This pattern also occurred for omnivores that belong to Icteridae, i.e. Austral Blackbird (*Curaeus curaeus*), and Muscicapidae, i.e. Austral Thrush (*Turdus falcklandii*), and for frugivores that belong to Psittaciformes: Psittacidae, i.e. Austral Parakeet (*Enicognathus ferrugineus*), and to Columbiformes: Columbidae, i.e. Chilean Pigeon (*Patagioenas araucana*). Species having a non-consistent crepuscular activity include insectivores that belong to Passeriformes of the families Furnariidae, i.e. White-throated Treerunner (*Pygarrhichas albogularis*), Rhynocriptidae, i.e. Chucao Tapaculo (*S. rubecula*), and Hirundinidae, i.e. Chilean Swallow (*Tachycineta meyeni*) (Figure 3 and Table 1).

Fifteen species had at least 20 detections within a given sampled month allowing to obtain a detailed calling diel pattern (Figure 3). These species were all diurnal, most of which also showed crepuscular activity. The diel vocal patterns tend to show variations between months, as the number of hours in activity decreases with the shortening of the sunlight period. During this time period, species showing a relatively amodal pattern include a Passeriform omnivore that belongs to the family Tyrannidae, i.e. White-crested Elaenia (*E. albiceps*), a Passeriform insectivore that belongs to Rhinocryptidae, i.e. Chucao Tapaculo (*S. rubecula*), and the Apodiform nectarivore that belongs to Trochilidae, i.e. Green-backed Firecrown (*S. sephaniodes*). Unimodal-like patterns were observed for insectivores that belong to Passeriformes of the family Furnariidae, i.e. White-throated Treerunner (*P. albogularis*), and Hirundinidae, i.e. Chilean Swallow (*T. meyeni*), that showed more activity around 6 h after sunset, and for the Passeriform granivore that belongs to Thraupidae, i.e. Patagonian Sierra-finch (*Phrygilus patagonicus*), that showed more activity during morning hours. Bimodal patterns around hours of sunrise and sunset, although differing in peak height, occurred for Passeriform insectivores that belong to Furnariidae, i.e. Thorn-tailed Rayadito (*A. spincauda*) and Des Mur's Wiretail (*S. desmursii*), and to Rhinocryptidae, i.e. Ochre-flanked Tapaculo (*E. paradoxa*), Black-throated Huet-huet (*P. tarnii*) and Magellanic Tapaculo (*S. magellanicus*). This same pattern was observed for the Psittaciform frugivore that belongs to Psittacidae, i.e. Austral Parakeet (*E. ferrugineus*), for a Columbiform frugivore that belongs to Columbidae, i.e. Chilean Pigeon (*P. Araucana*), and for a Passeriform omnivore that belongs to Muscicapidae, i.e. Austral Thrush (*T. falcklandii*). Finally, a pattern with three peaks was observed for the omnivorous Passeriform that belongs to Icteridae, i.e. Austral Blackbird (*C. curaeus*).

The analyses of the overlap between calling activity patterns considered only species that had at least 20 detections within a sampled month. During January, 15 species were considered for the analysis. Considering the diet guild, seven out of eight insectivores that belong to the Passeriformes order tend to be clustered, with the exception of White-throated Treerunner (*P. albogularis*, Passeriformes: Furnariidae), however within the cluster an omnivore from the same order also occurs: Austral Thrush (*T. falcklandii*, Passeriformes: Muscicapidae), and two species that belong to different orders, i.e. the frugivore Austral Parakeet (*E. ferrugineus*, Psittaciformes: Psittacidae), and the nectarivore Green-backed Firecrown (*S. sephaniodes*, Apodiformes: Trochilidae). In February, 13 species were considered for the analysis and no clear clustering pattern considering diet guild or taxonomic group was observed. In March, six species were included, and no clear clustering patterns were observed (Figure 4).

Table 1. Selection ratios (Wi) and test of non-random use of time periods. Species having at least 20 detections during the entire monitoring interval were considered for the analyses. Species are listed in decreasing order according to the number of detections (see Figure 3).

| Species	Order	Family	Diet guild	Wi Cre ± SE	Wi Diu ± SE	Wi Noc ± SE	Khi2L	df	p-val
Scelorchilus rubecula	Passeriformes	Rhinocryptidae	I	1.004 ± 0.062	1.658 ± 0.020	0.002 ± 0.002	1104.487	2	<0.001
Sephanoides sephaniodes	Apodiformes	Trochilidae	N	0.813 ± 0.071	1.723 ± 0.023	0.000 ± 0.000	746.197	2	<0.001
Elaenia albiceps	Passeriformes	Tyrannidae	O	0.820 ± 0.075	1.716 ± 0.025	0.008 ± 0.006	648.633	2	<0.001
Aphrastura spinicauda	Passeriformes	Furnariidae	I	1.322 ± 0.124	1.550 ± 0.041	0.007 ± 0.007	315.836	2	<0.001
Pteroptochos tarnii	Passeriformes	Rhinocryptidae	I	2.130 ± 0.157	1.281 ± 0.052	0.009 ± 0.009	277.488	2	<0.001
Turdus falcklandii	Passeriformes	Muscicapidae	O	2.290 ± 0.168	1.221 ± 0.056	0.020 ± 0.014	248.685	2	<0.001
Scytalopus magellanicus	Passeriformes	Rhinocryptidae	I	1.353 ± 0.199	1.544 ± 0.066	0.000 ± 0.000	129.537	2	<0.001
Patagioenas araucana	Columbiformes	Columbidae	F	1.282 ± 0.211	1.568 ± 0.070	0.000 ± 0.000	110.639	2	<0.001
Eugralla paradoxa	Passeriformes	Rhinocryptidae	I	1.381 ± 0.218	1.535 ± 0.072	0.000 ± 0.000	109.149	2	<0.001
Tachycineta meyeni	Passeriformes	Hirundinidae	I	1.098 ± 0.207	1.613 ± 0.070	0.024 ± 0.024	94.359	2	<0.001
Enicognathus ferrugineus	Psittaciformes	Psittacidae	F	1.927 ± 0.277	1.354 ± 0.092	0.000 ± 0.000	85.735	2	<0.001
Sylviorthorhynchus desmursii	Passeriformes	Furnariidae	I	1.629 ± 0.273	1.453 ± 0.090	0.000 ± 0.000	77.667	2	<0.001
Pygarrhichas albogularis	Passeriformes	Furnariidae	I	1.002 ± 0.305	1.660 ± 0.101	0.000 ± 0.000	45.680	2	<0.001
Phrygilus patagonicus	Passeriformes	Thraupidae	G	0.694 ± 0.266	1.763 ± 0.088	0.000 ± 0.000	47.761	2	<0.001
Curaeus curaeus	Passeriformes	Icteridae	O	2.123 ± 0.493	1.289 ± 0.163	0.000 ± 0.000	29.244	2	<0.001
Strix rufipes	Strigiformes	Strigidae	C	1.823 ± 0.481	0.362 ± 0.134	1.552 ± 0.262	14.772	2	0.001
Glaucidium nana	Strigiformes	Strigidae	C	3.308 ± 0.669	0.199 ± 0.134	1.055 ± 0.321	20.612	2	<0.001

Abbreviations: Cre: crepuscular, Diu: Diurnal, Noc: Nocturnal, SE: Standard Error, C: carnivore, F: frugivore, G: granivore, I: insectivore, N: nectarivore, O: omnivore.
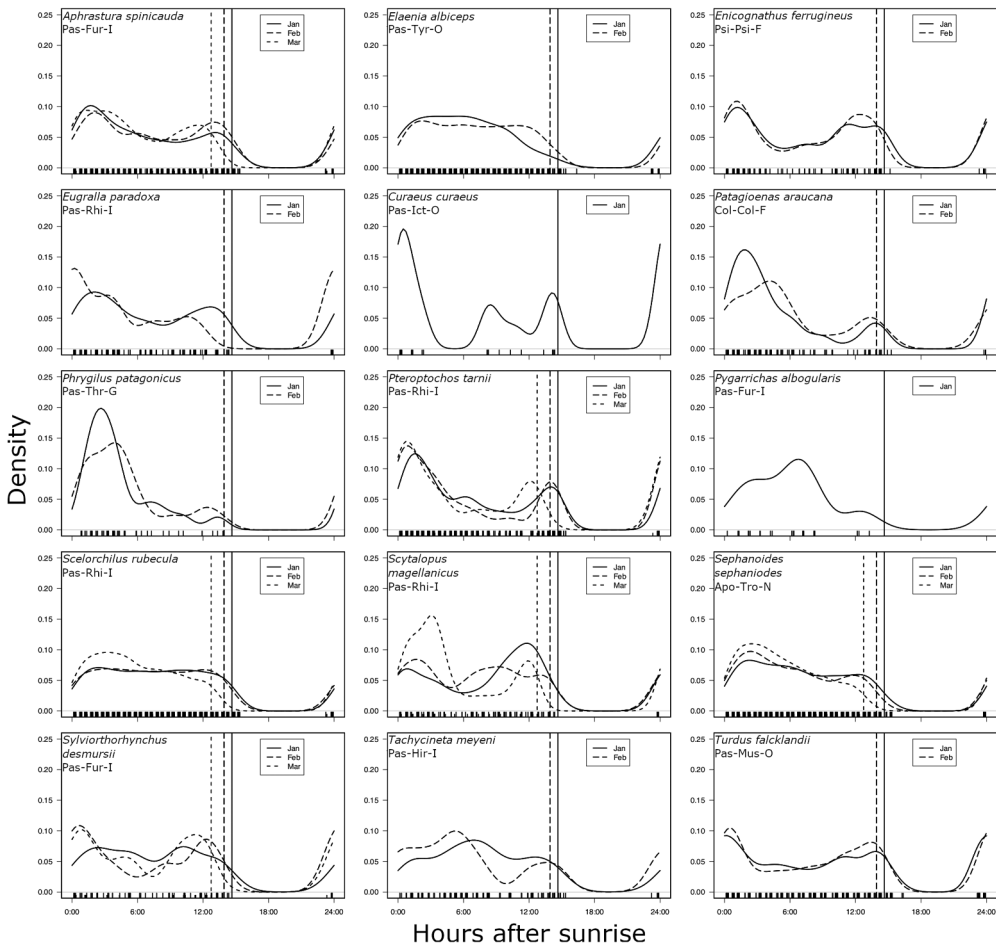
Figure 3. Kernel density functions of diel calling activity patterns of species having at least 20 detections within a sampled month. Vertical lines indicate the hour of sunset time. Below the scientific name of each species the abbreviations of the order – family - diet guild are provided. Order: Apo: Apodiformes, Col: Columbiformes, Pas: Passseriformes, Psi: Psittaciformes. Family: Col: Columbidae, Fur: Furnariidae, Hir: Hirundidae, Ict: Icteridae, Mus: Muscicapidae, Psi: Psittacidae, Rhi: Rhinocryptidae, Thr: Thraupidae, Tro: Trochilidae, Tyr: Tyrannidae. Diet guild: F: frugivore, G: granivore, I: insectivore, N: nectarivore, O: omnivore.

Discussion

Using autonomous recorder units (ARUs) we studied the summer vocal activity patterns of a bird assemblage from the Valdivian temperate rainforest, a recognised biodiversity hotspot located in southernmost South America (Myers et al. 2000). Our sampling procedure allowed to detect 26 bird species. Our results indicate that high richness levels are detected around sunrise and sunset. Also, within the bird assemblage studied, most birds show diurnal vocal activity, among which several were also active during crepuscular periods, and only two species had nocturnal vocal activity. Among diurnal birds with enough number of detections to perform a detailed description of diel calling patterns, our results did not show clear trends considering diet guild or taxonomic group.
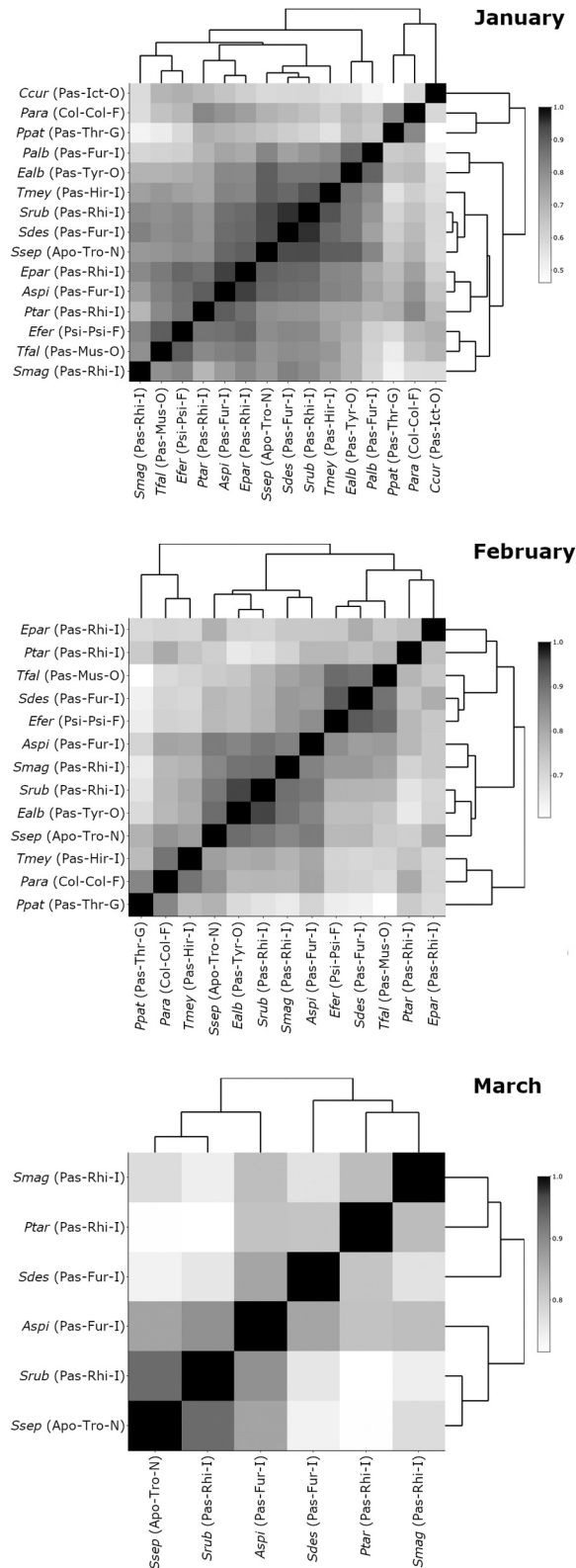
Figure 4. Overlap in calling activity patterns among birds during the three sampled months. Only species having at least 20 detections within a given month were included for the analysis. Gray scale indicate the overlap value between pairs of species. Dendrograms were obtained by hierarchical

The data indicate that more species are detected around sunrise and sunset, and the number of species detected is reduced towards the end of summer, during March. A reduction in detections may be associated with variations in calling behaviour depending on the stage of the reproductive period and on the migration process of some species (Jiménez et al. 2016; Norambuena and Muñoz-Pedreros 2017). A recent study in an urban wetland near the study site using ARUs and species detections through neural networks have reported variations in seasonal and diel acoustic activity of calling birds, including White-crested Elaenia (*E. albiceps*), a migrant species that was detected in our study (Morales et al. 2022). Although a study performed by Drake et al. (2021) in two continents reports that the efficiency of ARUs depends on the proportion of vocal species within the bird community, our sampling design yields estimates concordant with bird richness levels reported previously for the same forest ecosystem through point-counts (Vergara et al. 2010).

Most species in the bird assemblage showed diurnal vocal activity, several of which were also active during crepuscular periods. In general, these species belong to the Passeriformes order, including the rhinocryptid Chucao Tapaculo (*S. rubecula*), the species with the highest number of detections; however, other taxonomic groups are also represented, such as the Apodiformes order that include Green-backed Firecrown (*S. sephaniodes*), the second species with the highest detections. Considering diet guilds, most of these species are insectivores, but there are also omnivores and species that have a stricter plant-based diet. Regarding nocturnal calling patterns, the two registered species with carnivore diet of Strigiformes order, i.e. Rufous-legged Owl (*S. rufipes*) and Austral Pygmy-owl (*G. nana*), showed crepuscular and nocturnal calling patterns. These two species also showed crepuscular patterns. Therefore, our results indicate within the studied bird assemblage, only species with a carnivore diet that belong to the Strigiformes order show nocturnal vocal patterns. A previous study performed by Norambuena and Muñoz-Pedreros (2012) reported that the calling of Austral Pygmy-owl reaches a peak around mid-morning, however this study was performed by direct observations between 0700 and 1900 h and in another locality, i.e. Cerro Ñielol, a protected wildlife area, that is nearby Temuco city, a main urban complex in southern Chile. It will be of interest to study variations in calling patterns using ARUs in a 24-h schedule in different localities, as recent studies comparing urban and rural settings have revealed different bird vocal activity patterns (Bermúdez-Cuamatzin et al. 2020).

clustering. Abbreviations of species scientific names are followed by abbreviations of the order – family - diet guild within parenthesis. Scientific names: Aspi: *Aphrastura spinicauda*, Ccur: *Curaeus curaeus*, Ealb: *Elaenia albiceps*, Efer: *Enicognathus ferrugineus*, Epar: *Eugralla paradoxa*, Para: *Patagioenas araucana*, Ppat: *Phrygilus patagonicus*, Ptar: *Pteroptochos tarnii*, Palb: *Pygarrichas albogularis*, Srub: *Scelorchilus rubecula*, Smag: *Scytalopus magellanicus*, Ssep: *Sephanoides sephaniodes*, Sdes: *Sylviorthorhynchus desmursii*, Tmey: *Tachycineta meyeni*, Tfal: *Turdus falcklandii*. Order: Apo: Apodiformes, Col: Columbiformes, Pas: Passseriformes, Psi: Psittaciformes. Family: Col: Columbidae, Fur: Furnariidae, Hir: Hirundidae, Ict: Icteridae, Mus: Muscicapidae, Psi: Psittacidae, Rhi: Rhinocryptidae, Thr: Thraupidae, Tro: Trochilidae, Tyr: Tyrannidae. Diet guild: F: frugivore, G: granivore, I: insectivore, N: nectarivore, O: omnivore.

Fifteen species had a sufficient number of detections to perform a detailed description of diel vocal activity patterns (i.e. at least 20 detections within a sampled month). These were all diurnal birds, and some also showed crepuscular activity. Different patterns were observed, including species having marked peaks and species having seemingly amodal patterns. While we know that calling patterns can be associated with types of preferred food and visual capabilities, and that diurnal birds tend to concentrate territorial displays and foraging during early morning and late in afternoon, departures of this bimodal pattern to an amodal pattern have been reported (Staicer et al. 1996; Gil and Llusia 2020). It is likely that species that feed on other animals show modal patterns that are associated with the activity of their prey, whereas birds that fed on plant-based resources are expected to show more amodal patterns of activity (e.g. Reyes-Arriagada et al. 2015). Our results show departures of this expectation. Indeed, considering the insectivore guild, 5 out of 8 species showed a bimodal pattern, which was also observed for two frugivores and one omnivore. Furthermore, an amodal pattern was observed for one insectivore, the only nectarivore and one omnivore species. Moreover, there was no calling pattern of diurnal species that was exclusively observed in a determined group. These results agree with the overlapping calling patterns between species, which did not show clear and consistent clustering trends considering diet guild or taxonomic group. It is likely that a more detailed description and knowledge of dietary items consumed by each species would provide relevant insights into our results. For instance, species normally classified as insectivores can also feed on vegetal resources (see Martínez-Piña and González-Cifuentes 2017), and these variations in dietary items may require a finer classification to explain activity patterns.

The activity patterns of diurnal birds are affected by several factors. For passerine birds, bimodal patterns are expected during high-temperature seasons due to effects on metabolic expenditure, and also when food availability interrupts foraging to reduce predation risks (see Reyes-Arriagada et al. 2015). Reyes-Arriagada et al. (2015) performed a study on the diel foraging/movement activity patterns (using captures through mist-nets) of three passerine species included in our study, but their research was conducted in Cape Horn, the southernmost distribution limit of these species. Within the forest and during the summer, they found a unimodal pattern around midday for the insectivore Thorn-tailed Rayadito (*A. spinicauda*), and a homogeneous pattern was observed for the granivore Chilean Pigeon (*P. patagonicus*) and for the omnivore White-crested Elaenia (*E. albiceps*). Interestingly, for the insectivore species, when comparing our results of vocal activity and the foraging activity patterns reported by these authors, the timing of peaks do not match, indicating no overlap between these different types of activity. In the case of the omnivore species, our results of vocal activity and the foraging activity reported by these authors follow the same amodal pattern; and in the granivore species, while vocal activity showed a marked unimodal pattern, foraging activity was amodal. These trends are likely to be associated to the mixed or strict type of diet, i.e. omnivore and granivore, that may affect food availability. Although these differences may support the notion that calling patterns for some species may be restricted by foraging activity and food profitability (reviewed in Gil and Llusia 2020), latitudinal effects and potential differences in predator pressures should also be acknowledged. For instance, a study using camera traps performed by Delibes-Mateos et al. (2014) in a natural reserve located southern relative to our study site showed bimodal

patterns for Chucao Tapaculo (*S. rubecula*) and Black-throated Huet-huet (*P. tarnii*), which may be related to the activity of a predator, i.e. *Leopardus guigna*. In partial contrast, our data indicate that for Chucao Tapaculo the vocal activity tends to be relatively constant during the hours with sunlight. Future studies involving simultaneously different sampling methodologies at different localities are needed to disentangle the factors that may explain differences among species and diet guilds.

Future studies should include analyses of the acoustic properties of the different call types emitted by each species, the time at which these are emitted and the height at which each species vocalise. This is because habitat characteristics and weather conditions impose differential constraints on signal propagation that may shape the vocal behaviour of birds (reviewed in Slabbekoorn 2004). These factors also influence the effectiveness of acoustic monitoring using ARUs as has been observed in a playback study in New Zealand, where acoustic properties of vocalisations produced by different species affect differentially the recordings, and therefore their detection (Priyadarshani et al. 2018). In addition, acoustic competition between species within a community should also be considered, as has been observed in the tropical bird *Pharomachrus mocinno* where acoustic overlap with other birds was related to similarity in food resources and phylogenetic relationships (Bolaños-Sittler et al. 2021).

Reports on detailed activity patterns (i.e. 24-h) of birds are increasing (Jahn et al. 2017; Pérez-Granados and Schuchmann 2020, 2021, 2022); however, for a bird forest assembly these are still scant. This is likely due to the current difficulties in analysing large amounts of audio recording data (Gibb et al. 2019). A recent study performed in urban wetlands near the study site has proposed a method for species recognition using convolutional neural networks (Morales et al. 2022), and we have previously addressed the issue of analysing large acoustic data sets through acoustic diversity indices to assess variations in bird species richness over time (Moreno-Gómez et al. 2019).

In conclusion, ARUs constitute a useful tool to study the vocal activity patterns of birds from the Valdivian temperate rainforest, where high richness levels are detected around sunrise and sunset. Our results indicate that most birds show diurnal vocal activity, among which several were also in activity during crepuscular periods, and that only two species from the Strigiformes over show nocturnal vocal activity. Among diurnal birds with enough number of detections to perform a detailed description of diel calling patterns, our results did not show clear trends considering feeding guild or taxonomic group. We expect that our study will encourage future research to increase the understanding on the factors influencing vocal activity patterns, as well as population and community trends in this biodiversity hotspot.

Disclosure statement

Funding

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References

Amico GC, García D, Rodríguez-Cabal MA. 2008. Spatial structure and scale-dependent micro-habitat use of endemic "tapaculos" (Rhinocryptidae) in a temperate forest of southern South America. Ecol Austral. 18:169–180.

Armesto JJ, Smith-Ramírez C, Sabag C. 1996. The importance of plant-bird mutualisms in the temperate rainforest of southern South America. In: Lawford RG, Fuentes E, Alaback PB, editors. High-latitude rainforests and associated ecosystems of the west coast of the Americas. New York (NY): Springer; p. 248–265.

Bartheld J, Moreno-Gómez FN, Soto-Gamboa M, Silva-Escobar AA, Suazo CG. 2011. Monitoreo Acústico de Aves y Anfibios en el Bosque Costero Valdiviano. Valdivia (Chile): Bartheld Villagra, José Luis.

Bereczki K, Ódor P, Csóka G, Mag Z, Báldi A. 2014. Effects of forest heterogeneity on the efficiency of caterpillar control service provided by birds in temperate oak forests. For Ecol Manag. 327:96–105. doi: 10.1016/j.foreco.2014.05.001.

Berg KS, Brumfield RT, Apanius V. 2006. Phylogenetic and ecological determinants of the neotropical dawn chorus. Proc R Soc B. 273(1589):999–1005. doi: 10.1098/rspb.2005.3410.

Bermúdez-Cuamatzin E, Delamore Z, Verbeek L, Kremer C, Slabbekoorn H. 2020. Variation in diurnal patterns of singing activity between urban and rural great tits. Front Ecol Evol. 8:246. doi: 10.3389/fevo.2020.00246.

Bolaños-Sittler P, Aubin T, Padilla A, Sueur J. 2021. Acoustic competition within a tropical bird community: the case of the Resplendent Quetzal *Pharomachrus mocinno* in Guatemala. J Trop Ecol. 37(6):291–301. doi: 10.1017/S0266467421000420.

Brooks ME, Kristensen K, Van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Mächler M, Bolker BM. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J. 9(2):378–400. doi: 10.32614/RJ-2017-066.

Bu H, Wang F, McShea WJ, Lu Z, Wang D, Li S, Allen BL. 2016. Spatial co-occurrence and activity patterns of mesocarnivores in the temperate forests of southwest China. PloS One. 11(10): e0164271. doi: 10.1371/journal.pone.0164271.

Calenge C. 2006. The package "adehabitat" for the R software: a tool for the analysis of space and habitat use by animals. Ecol Modell. 197(3–4):516–519. doi: 10.1016/j.ecolmodel.2006.03.017.

Caravaggi A, Gatta M, Vallely MC, Hogg K, Freeman M, Fadaei E, Dick JTA, Montgomery WI, Reid R, Tosh DG. 2018. Seasonal and predator-prey effects on circadian activity of free-ranging mammals revealed by camera traps. PeerJ. 6:e5827. doi: 10.7717/peerj.5827.

Clément M, Shonfield J, Bayne EM, Baldwin R, Barrett K. 2021. Quantifying vocal activity and detection probability to inform survey methods for Barred Owls (*Strix varia*). J Raptor Res. 55 (1):45–55. doi: 10.3356/0892-1016-55.1.45.

Clout MN, Hay JR. 1989. The importance of birds as browsers, pollinators and seed dispersers in New Zealand forests. N Z J Ecol. 12:27–33.

Darras K, Batáry P, Furnas B, Celis–Murillo A, Van Wilgenburg SL, Mulyani YA, Tscharntke T, Willis S. 2018. Comparing the sampling performance of sound recorders versus point counts in bird surveys: a meta–analysis. J Appl Ecol. 55(6):2575–2586. doi: 10.1111/1365-2664.13229.

Delibes-Mateos M, Díaz-Ruiz F, Caro J, Ferreras P. 2014. Activity patterns of the vulnerable guiña (*Leopardus guigna*) and its main prey in the Valdivian rainforest of southern Chile. Mamm Biol. 79(6):393–397. doi: 10.1016/j.mambio.2014.04.006.

Díaz IA. 2005. Historia natural, diversidad y conservación de las aves en bosques de la Cordillera de la Costa de la región de Los Lagos. In: Smith-Ramirez C, Armesto JJ, Valdovinos C, editors. Historia, biodiversidad y ecología de los bosques costeros de Chile. Santiago (Chile): Editorial Universitaria; p. 456–466.

Drake A, de Zwaan DR, Altamirano TA, Wilson S, Hick K, Bravo C, Ibarra JT, Martin K. 2021. Combining point counts and autonomous recording units improves avian survey efficacy across elevational gradients on two continents. Ecol Evol. 11(13):8654–8682. doi: 10.1002/ece3.7678.

Ehnes M, Dech JP, Foote JR. 2018. Seasonal changes in acoustic detection of forest birds. J Ecoacoustics. 2(1):1–1. doi: 10.22261/jea.qvdzo7.

Galili T, O'Callaghan A, Sidi J, Sievert C. 2017. Heatmaply: an R package for creating interactive cluster heatmaps for online publishing. Bioinformatics. btx657. doi: 10.1093/bioinformatics/btx657.

Garamszegi LZ, Møller AP, Erritzøe J. 2002. Coevolving avian eye size and brain size in relation to prey capture and nocturnality. Proc Royal Soc B. 269(1494):961–967. doi: 10.1098/rspb.2002.1967.

Gibb R, Browning E, Glover–Kapfer P, Jones KE, Börger L. 2019. Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. Methods Ecol Evol. 10 (2):169–185. doi: 10.1111/2041-210X.13101.

Gil D, Llusia D. 2020. The bird dawn chorus revisited. In: Aubin T, Mathevon N, editors. Coding strategies in vertebrate acoustic communication. Cham: Springer; p. 45–90.

Hsieh TC, Ma KH, Chao A. 2022. iNEXT: iNterpolation and EXTrapolation for species diversity. R package version 3.0.0. http://chao.stat.nthu.edu.tw/wordpress/software-download/.

Ikeda T, Uchida K, Matsuura Y, Takahashi H, Yoshida T, Kaji K, Koizumi I, Yamazaki S. 2016. Seasonal and diel activity patterns of eight sympatric mammals in northern Japan revealed by an intensive camera-trap survey. PloS One. 11(10):e0163602. doi: 10.1371/journal.pone.0163602.

Jahn O, Ganchev TD, Marques MI, Schuchmann KL, Fine ML. 2017. Automated sound recognition provides insights into the behavioral ecology of a tropical bird. PloS One. 12(1):e0169041. doi: 10.1371/journal.pone.0169041.

Jiménez JE, Jahn AE, Rozzi R, Seavy NE. 2016. First documented migration of individual White-crested Elaenias (*Elaenia albiceps chilensis*) in South America. Wilson J Ornithol. 128(2):419–425. doi: 10.1676/1559-4491-128.2.419.

Jiménez JE, Jaksic FM. 1993. Variación estacional de la dieta del caburé grande (*Glaucidium nanum*) en Chile y su relación con la abundancia de presas. El Hornero. 13(4):265–271. doi: 10.56178/eh.v13i4.1044.

Krause B, Farina A. 2016. Using ecoacoustic methods to survey the impacts of climate change on biodiversity. Biol Conserv. 195:245–254. doi: 10.1016/j.biocon.2016.01.013.

Kułaga K, Budka M. 2020. Nocturnal singing by diurnal birds in a temperate region of central Europe. J Ornithol. 161(4):1143–1152. doi: 10.1007/s10336-020-01794-5.

Kułaga K, Budka M, Pérez-García JM. 2019. Bird species detection by an observer and an autonomous sound recorder in two different environments: forest and farmland. PloS One. 14(2):e0211970. doi: 10.1371/journal.pone.0211970.

La VT. 2012. Diurnal and nocturnal birds vocalize at night: a review. Condor. 114:245–257.

Manly BFL, McDonald L, Thomas DL, McDonald TL, Erickson WP. 2004. Resource selection by animals: statistical design and analysis for field studies. Dordrecht: Springer Science & Business Media.

Marler PR, Slabbekoorn H. 2004. Nature's music: the science of birdsong. USA: Elsevier.

Martinez DR, Jaksic FM. 1996. Habitat, relative abundance, and diet of rufous-legged owls (*Strix rufipes* King) in temperate forest remnants of southern Chile. Écoscience. 3(3):259–263. doi: 10.1080/11956860.1996.11682340.

Martinez DR, Jaksic FM. 1997. Selective predation on scansorial and arboreal mammals by rufous-legged owls (*Strix rufipes*) in southern Chilean rainforest. J Raptor Res. 31:370–375.

Martínez-Piña D, González-Cifuentes G. 2017. Aves de Chile: Guía de Campo y Breve Historia Natural. Santiago (Chile): Ediciones del Naturalista.

Morales G, Vargas V, Espejo D, Poblete V, Tomasevic JA, Otondo F, Navedo JG. 2022. Method for passive acoustic monitoring of bird communities using UMAP and a deep neural network. Ecol Inform. 72:101909. doi: 10.1016/j.ecoinf.2022.101909.

Moreno-Gómez FN, Bartheld J, Silva-Escobar AA, Briones R, Márquez R, Penna M. 2019. Evaluating acoustic indices in the Valdivian rainforest, a biodiversity hotspot in South America. Ecol Indic. 103:1–8. doi: 10.1016/j.ecolind.2019.03.024.

Moreno-Gómez FN, Sueur J, Soto-Gamboa M, Penna M. 2013. Female frog auditory sensitivity, male calls, and background noise: potential influences on the evolution of a peculiar matched filter. Biol J Linn Soc Lond. 110(4):814–827. doi: 10.1111/bij.12156.

Moreno RA, Zamora R, Herrera MA. 2014. Habitat selection of endemic birds in temperate forests in a biodiversity "Hotspot". For Syst. 23:216–224. doi: 10.5424/fs/2014232-03700.

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature. 403(6772):853–858. doi: 10.1038/35002501.

Norambuena HV, Muñoz-Pedreros A. 2012. Diurnal activity of the Austral Pygmy Owl (*Glaucidium nana*) in southern Chile. Wilson J Ornithol. 124(3):633–635. doi: 10.1676/11-118.1.

Norambuena HV, Muñoz-Pedreros A. 2017. Detection and vocalisations of three owl species (strigiformes) in temperate rainforests of southern Chile. N Z J Zool. 45:121–135.

Penna M, Veloso A. 1990. Vocal diversity in frogs of the South American temperate forest. J Herpetol. 24(1):23–33. doi: 10.2307/1564285.

Pérez-Granados C, Schuchmann KL. 2020. Diel and seasonal variations of vocal behavior of the Neotropical White-Tipped Dove (*Leptotila verreauxi*). Diversity. 12(10):402. doi: 10.3390/d12100402.

Pérez-Granados C, Schuchmann KL. 2021. Passive acoustic monitoring of Chaco Chachalaca (*Ortalis canicollis*) over a year: vocal activity pattern and monitoring recommendations. Trop Conserv Sci. 14:19400829211058295. doi: 10.1177/19400829211058295.

Pérez-Granados C, Schuchmann KL. 2022. Automated signal recognition as a useful tool for monitoring little-studied species: the case of the band-tailed nighthawk. Ecol Inform. 72:101861. doi: 10.1016/j.ecoinf.2022.101861.

Priyadarshani N, Castro I, Marsland S. 2018. The impact of environmental factors in birdsong acquisition using automated recorders. Ecol Evol. 8(10):5016–5033. doi: 10.1002/ece3.3889.

R Core Team. 2021. R: a language and environment for statistical computing. Vienna (Austria): R Foundation for Statistical Computing. https://www.R-project.org/.

Reid S, Cornelius C, Barbosa O, Meynard C, Silva-García C, Marquet PA. 2002. Conservation of temperate forest birds in Chile: implications from the study of an isolated forest relict. Biodivers Conserv. 11(11):1975–1990. doi: 10.1023/A:1020838610330.

Reyes-Arriagada R, Jiménez JE, Rozzi R. 2015. Daily patterns of activity of passerine birds in a Magellanic sub-Antarctic forest at Omora park (55°S), Cape Horn Biosphere Reserve, Chile. Polar Biol. 38(3):401–411. doi: 10.1007/s00300-014-1596-5.

Ridout MS, Linkie M. 2009. Estimating overlap of daily activity patterns from camera trap data. J Agric Biol Environ Stat. 14(3):322–337. doi: 10.1198/jabes.2009.08038.

Rowcliffe M. 2021. Activity: animal activity statistics. R package version 1.3.1. https://CRAN.R-project.org/package=activity .

Schwartz CC, Cain SL, Podruzny S, Cherry S, Frattaroli L. 2010. Contrasting activity patterns of sympatric and allopatric black and grizzly bears. J Wildl Manage. 74(8):1628–1638. doi: 10.2193/2009-571.

Slabbekoorn H. 2004. Singing in the wild: the ecology of birdsong. In: Marler P, Slabbekoorn H, editors. Nature's music: the science of birdsong. USA: Elsevier; p. 178–205.

Staicer CA, Spector DA, Horn AG. 1996. The dawn chorus and other diel patterns in acoustic signaling. In: Kroodsma DE, Miller EH, editors. Ecology and evolution of acoustic communication in birds. Ithaca (NY): Cornell University Press; p. 426–453.

Sugai LSM, Silva TSF, Ribeiro JW Jr, Llusia D. 2019. Terrestrial passive acoustic monitoring: review and perspectives. BioScience. 69(1):15–25. doi: 10.1093/biosci/biy147.

Thieurmel B, Elmarhraoui A. 2019. Suncalc: compute sun position, sunlight phases, moon position and lunar phase. R package version 0.5.0. https://CRAN.R-project.org/package=suncalc.

Vergara PM, Jiménez JE, Schlatter RP. 2010. Effective point-count duration for estimating bird species' richness in Chilean forests. Zool Stud. 49:381–391.

Weisberg S. 2019. An R Companion to Applied Regression. 3rd ed. Thousand Oaks CA: Sage.

Willson MF. 2004. Loss of habitat connectivity hinders pair formation and juvenile dispersal of chucao tapaculos in Chilean rainforest. Condor. 106(1):166–171. doi: 10.1093/condor/106.1.166.