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Seasonal acoustic behavior of blue whales (*Balaenoptera musculus*) in the Gulf of California, Mexico

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ABSTRACT

Six years of passive acoustic monitoring data from the Gulf of California reveal seasonality and movements for the northeastern Pacific blue whales. Three sites were studied, one from the southern (Punta Pescadero) and two from the northern (Isla Tiburon and Canal de Ballenas) regions. A total of 4,953 h were analyzed, and 15,539 blue whale calls were detected, of which 2,723 (18%) were A calls, 11,249 were B calls (72%), and 1,567 were D calls (10%). A and B calls were produced both as song units (2,524) or AB singular calls (2,026). The high rate of songs and their seasonality suggest that the GC is a winter-breeding ground. A shift from AB call predominance in winter, to D calls in spring and early summer, especially at the entrance of the GC, suggests the importance of this area for reproduction and foraging. Analysis of calling frequency suggests a clear movement of blue whales from the southern region (Punta Pescadero) to the northern regions (Canal de Ballenas and Isla Tiburon), with subsequent southern movement in March. The seasonality and mobility of blue whales in the Gulf of California, inferred from their calling, contributes to the ecological understanding of this population.

Key words: northeastern Pacific blue whales, *Balaenoptera musculus*, Gulf of California, winter breeding season, call, seasonality, passive acoustic monitoring.

The blue whale (*Balaenoptera musculus*) is a cosmopolitan species whose vocal repertoire has been widely studied. Their distinctive song patterns have allowed differentiation into ten populations around the world (McDonald *et al*. 2006, Frank and Ferries 2011). In the North Pacific, differentiation between a western and an eastern population was shown using acoustic data (Stafford *et al*. 1999, 2001) and has facilitated the estimation of preexploitation abundance levels for both populations (Monnahan *et al*. 2014). The northeastern Pacific blue whale population is identified as the most recovered of all (Sears and Calambokidis 2002) with an estimate of around 2,500 individuals (Calambokidis and Barlow 2004) and a known distribution in the

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northeastern Pacific, from the Aleutian Islands and the Gulf of Alaska to Baja California, Mexico (Rice 1974). This population follows a pattern of winter migration to the Costa Rica Dome (Mate *et al*. 1999, Stafford *et al*. 1999, Bailey *et al*. 2009) and to the Gulf of California (Calambokidis *et al*. 1990, Bailey *et al*. 2009). An estimated 300 blue whales (CV = 48.4%) migrate into the Gulf of California annually and this area is an important nursing and probable breeding site as well as a foraging ground during winter and spring (Gendron 2002).

Three distinctive calls (A, B, and D) have been identified for this population. The A call is composed of low frequency pulses that have durations of 20 s and a fundamental frequency of around 15 Hz, accompanied by strong overtones near to 90 Hz. The B call is a tonal signal with duration of 20 s with strong harmonics, especially the third (48 Hz), which is typically the most intense. The D call is a short down swept pulse with frequencies from 98 Hz to 25 Hz and duration of 1–4 s (Thompson *et al*. 1996). The A and B calls have been found in pairs of units, named AB singular calls, or as components of a song phrase (Oleson *et al*. 2007*a*). Both types of calls are produced by males; while songs are found only in traveling solitary individuals it is presumed to function in reproduction, the AB singular calls are found associated with different behaviors including feeding, milling, resting, and traveling, and in presence of more than one whale (Oleson *et al*. 2007*a*). The D calls have been recorded from both sexes and have been suggested to serve as contact calls (McDonald *et al*. 2001, Oleson *et al*. 2007a). In the feeding grounds off California, seasonality of blue whale calls is generally observed from early summer to winter (June–December), with peaks in late summer to early fall (September–October) (Stafford *et al*. 2001, Burtenshaw *et al*. 2004, Oleson 2005, Wiggins *et al*. 2005, Širović *et al*. 2015). In the Costa Rica Dome, blue whale calls were found throughout the year, but more frequently recorded from February to May (Stafford *et al*. 2001).

Apart from the studies published by Oleson *et al*. (2007*a*, *b*) on blue whales recorded off California, little research has been focused on the seasonal acoustic repertoire of this species. Our objective in this study is to use acoustic information to better understand seasonality and movements of blue whales within the Gulf of California, a breeding ground and highly relevant region in the life history of the species, based on their entire acoustic repertoire.

Materials and Methods

Data Collection

Acoustic recordings were collected with a single moored autonomous recorder (HARP: high-frequency acoustic recording package; Wiggins and Hildebrand 2007), deployed in different years, and at various sites in the Gulf of California (Fig. 1): southern region, Punta Pescadero (PP) (2005–2007); northern region, Isla Tiburon (IT) (2007–2008), and Canal de Ballenas (CB) (2008–2010). The HARP consists of a frame that is bottom-mounted, with the hydrophone tethered above the frame. The recorders were equipped with an omnidirectional sensor (ITC-1042, 10 Hz to 100 kHz (±2 dB) frequency response, −200 dB re V/µPa sensitivity; International Transducer Corporation, Santa Barbara, CA). The sensor was connected to a custom-built preamplifier board and a bandpass filter. The equipment was set to a duty cycle of 5 min of recordings with pauses of 15–30 min, depending on the site. All data were collected with a sample rate of 200 kHz and 16-bit quantization. Refer to Table 1 for HARP deployment information.

Figure 1. Gulf of California. HARP deployments in the southern region: Punta Pescadero (PP); northern region: Canal de Ballenas (CB), and Isla Tiburon (IT). Sites denoted by black diamonds.

Call Detection

Recordings were first decimated to a 2 kHz sampling rate to facilitate processing, and long-term spectral averages (LTSAs) were created with a time resolution of 5 s and 1 Hz frequency bands (Wiggins and Hildebrand 2007). *Triton*, a custom-made Matlab-based program (Wiggins and Hildebrand 2007), was used to plot the LTSAs in a window of 2 h of data, over a frequency range of 0–300 Hz, where blue whale calls A, B, and D were visually searched. If a call was found, it was more closely examined in a window of 60 s and a frequency range of 0–200 Hz, and once confirmed, the call type and detection time (start and end) were logged, creating a database for subsequent analyses. Next, a distinction between songs and AB singular calls was made, with songs defined as a stereotypical sequences of calls or phrases (one or more song units) that occur in a repeated pattern (McDonald *et al.* 2006), unlike the AB singular calls, which don't have a defined pattern. These include the A unit and/or B unit, the A unit not followed immediately by a B unit, the B unit without a preceding A unit, or a single AB call pair (Oleson *et al.* 2007*a*). In order to identify a song, we used the method of Oleson *et al.* (2007*b*) which consists of picking units B occurring as a part of a regular sequence from eight randomly chosen days and calculating the interval between successive units. However, we modified the method by adding the A unit in the different sequences, and using 30 audio files randomly chosen per year. We obtained intervals between the A unit and the consecutive B unit, for consecutive B units and for the B unit with interspersed A unit (when the A unit was

Table 1. HARP deployment details with recording start and end dates spanning multiple deployments, geographic locations, depths, recording schedule and total recording duration. Recording schedule is presented as the recording period (5 min) over the total time per cycle (15–30 min). Total recording duration is related to the number of hours obtained after accounting for the duty cycle and hours with noise masking.

Site	Recording Start	Recording end	Longitude (W)	Latitude (N)	Depth (m)	Recording schedule (min)	Total recording duration (h)
Punta Pescadero (PP)	16 May 2005	30 Sep 2005	109°37.80′	23°49.82′	659	5/25	659
	27 Nov 2005	8 Feb 2006	109°41.03′	23°54.86′	783	5/30	381
	7 Feb 2006	5 Aug 2006	109°37.66′	23°49.64′	690	5/25	852
	10 Dec 2006	5 Jun 2007	109°37.68′	23°49.44′	750	5/25	842
Isla Tiburon (IT)	20 Jun 2007	7 Dec 2007	112°30.30′	28°36.44′	400	5/20	445
	27 Jan 2008	17 Mar 2008	112°30.46′	28°36.38′	400	5/20	162
Canal de Ballenas (CB)	8 Aug 2008	25 Dec 2008	113°22.55′	29°01.61′	690	5/20	345
	26 Apr 2009	12 Sep 2009	113°22.53′	29°01.63′	690	5/15	740
	7 Dec 2009	18 May 2010	113°22.52′	29°01.65′	690	5/15	527

not recorded due to its low intensity). Blue whale units occurring at different intervals from those defined above were classified as AB singular calls.

Since there were no continuous recordings, the songs were manually picked for each year, counting each song within each 5 min window and averaged over a day. This method allowed counting of the singers and detecting and classifying overlapping songs due to the presence of more than one singing whale.

Data Treatment and Standardization

To obtain the recording duration, we standardized the data prior to the analysis since the 6 yr sampled did not include the same number of days and because the recordings were not continuous but were duty cycled. Hours for each deployment were obtained by dividing this number into the number of recording cycles; the result was multiplied by 24 h obtaining the real recording duration for each month, year, and recording site. When we found low frequency noise (0–150 Hz) in the recordings that could mask the blue whale calls, the hours of noise were removed from the analyses. In order to obtain complete seasonal time series, we pooled monthly recording from consecutive years per region.

Vocal Patterns

The relative seasonality was evaluated using the rate of each call type, which was obtained by dividing the number of calls per day (taking into account the recording cycle and extracting the masking hours) per each month of the year. We took astronomical seasons to mark the beginning and end of seasons in a year for the Northern Hemisphere. These rates were plotted to determine seasonal call trends, and to test for differences among the three sites and among months within each site using a nonparametric Kruskal-Wallis analysis with the software Statistica 7.

Results

A total of 7,376 h of recording were obtained between 2005 and 2010, of which only recordings without masking by environmental noise were used in the analysis, giving a total of 4,953 h. From these, 2,734 h (55%) were recorded in the southern region of PP, and 2,219 h from the northern region; 607 h (12%) from IT, and 1,612 h (33%) from CB (Table 1). A total of 15,539 blue whale calls were detected of which 2,723 (18%) were A call, 11,249 (72%) corresponded to B call, and 1,567 (10%) were D call. We found mean (± SD) intervals that were consistent for songs (Table 2). Once A and B units were integrated into songs or taken as AB singular calls, we obtained 3,305 songs and 2,113 AB singular calls. Overall, the songs were the most common blue whale call type registered during this study. The call rate for each month and per site was highly variable: 0.06–37.40 songs per day, 0.06–23.20 AB singular calls per day and 0.14–12.20 D calls per day (Table 3); with significant differences between sites (KW = 27.46, $P < 0.05$).

The original results prior to pooling showed a seasonal tendency in call rate; songs and AB singular calls were detected from November to April with the highest rates between December and February, decreasing until March (<50% of calls), while D call rate showed an inverse pattern, with similar rate as songs in February and dominance over the songs at the end of the season at PP (Fig. 2).

Table 2. Intervals (in seconds) between units consistent for songs.

Units	Interval (s)
A consecutive B	31.2 ± 2[a]
Consecutive Bs	40.2 ± 2
B with interspersed A	117.8 ± 4.5

[a]Mean ± SD.

After pooling, the call rate differences per sites persisted (KW = 24.38, $P < 0.05$) (Table 3). In the southern region at site PP, December and January showed the highest call rate for songs (10.18 and 12.56 detections per day), and AB singular calls (5.45 and 8.36 detections per day), decreasing as the season progressed, while D calls showed an inverse increasing pattern, reaching a peak of 11.42 detections per day in April, and decreasing until June (KW = 23.42, $P < 0.05$).

The rates of songs and AB singular calls were much higher in the northern regions of IT and CB compared to the southern site of PP. The first detections were recorded at IT in November (11.00 songs per day and 6.00 AB singular calls per day) with the highest rate in January (37.40 songs per day and 23.20 AB singular calls per day, KW = 24.18, $P < 0.05$); at CB, the calling peak was in December (26.30 songs per day and 15.27 AB singular calls per day, KW = 31.22, $P < 0.05$). The highest call rates in these northern sites were recorded during a 3 mo span (December–February), a much narrower detection period compared to the southern region of PP where the highest rates were recorded throughout 5 mo (December–April) (Table 3, Fig. 2). In contrast D call rates were similar in all sites (<10 d calls per day) but during different months. During 2007, D call rate was especially high at IT.

The different timing of blue whale calls among the three sites suggest a movement from the southern to the northern region over a seasonal cycle, reaching IT and CB in November, showing the highest activity in December and January when an overall calling peak was recorded, and finally a return to the south (PP) in March (Fig. 2).

Discussion

Our results on the seasonality of blue whale calls in the Gulf of California from November to July, coincide with previous seasonal visual observations (Gendron 2002). Acoustic data for blue whale presence in July at IT also is consistent with a few sightings in July (DG, unpublished data). Our study is based on the assumption that acoustic evidence reflects the presence of blue whales in the Gulf of California; however, we must acknowledge that this approach does not take into account non-calling individuals.

Although a comparison between breeding grounds would be desirable, the vocal analysis from the Costa Rica Dome (Stafford *et al.* 2001) was only based on A and B calls (D calls, songs, and AB singular calls were not analyzed). Hence, a direct comparison with the Gulf of California cannot be done, although for both regions most calls were concentrated over a 6 mo period and a different seasonality trend is observed. The earliest blue whale call in the Gulf of California was registered in November, while February holds the first detections for the Costa Rica Dome. Stafford *et al.* (2001) proposed that the Gulf of California was a way point along the blue

Table 3. Blue whale call detections per day after monthly pooling of songs (a), AB singular (b), and D calls (c), at the three sites under analysis: Punta Pescadero (PP), Isla Tiburon (IT), and Canal de Ballenas (CB).

	Site	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
(a)	PP	8.00	10.18	12.56	3.96	3.70	0.94	0	0	0	0	0	—
	IT	11.00	19.7	37.40	10.85	2.00	—	—	—	0	0	0	0
	CB	1.00	26.30	17.55	8.20	3.00	0.06	0	0	0	0	0	0
(b)	PP	1.00	5.45	8.36	3.77	3.29	1.57	0	0	0	0	0	—
	IT	6.00	3.00	23.20	9.44	3.00	—	—	—	0	0	0	0
	CB	6.00	15.27	10.20	5.30	2.30	0.06	0	0	0	0	0	0
(c)	PP	0	0.22	1.59	2.62	8.11	11.42	5.68	3.33	0	0	0	—
	IT	0	0.14	12.20	8.11	5.00	—	—	1.00	25.50	0	0	0
	CB	0	2.08	6.30	1.60	1.66	2.40	0	0	0	0	0	0

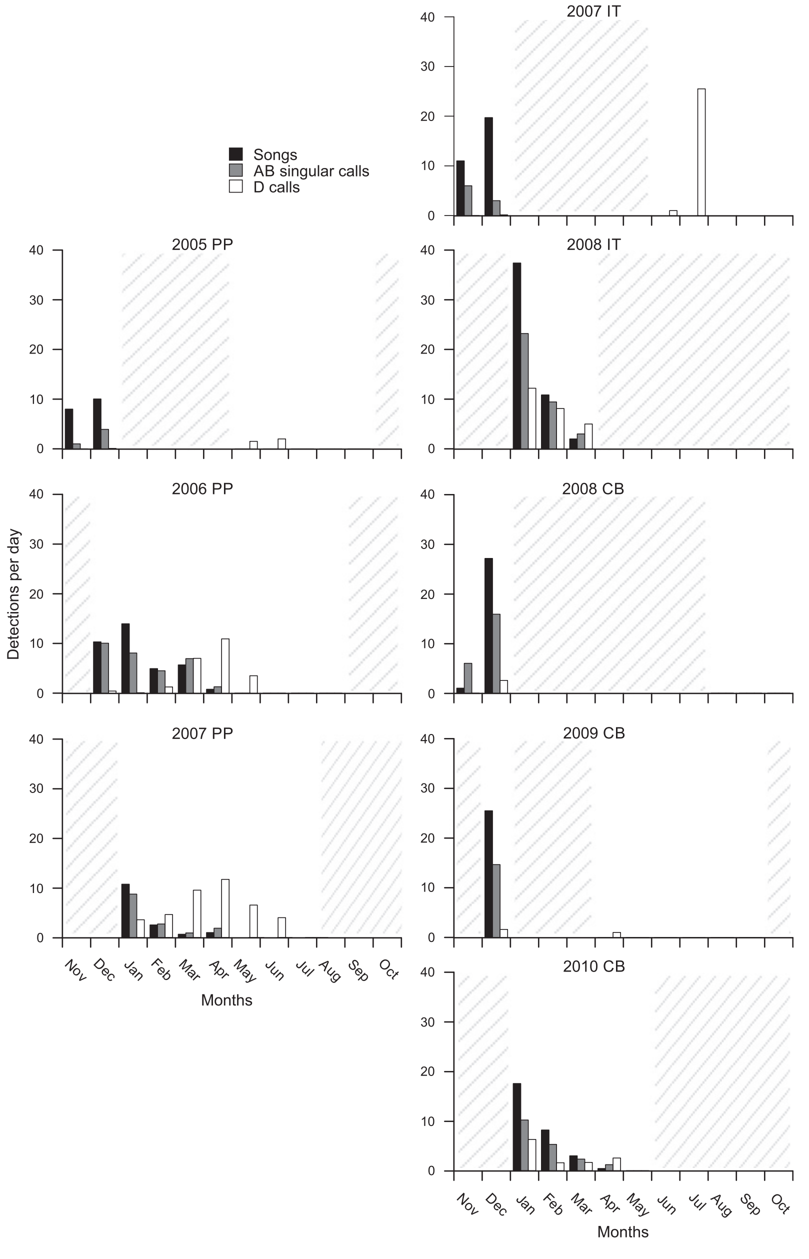

Figure 2. Blue whale call detections per day (songs, AB singular calls, and D calls) are shown per month and year at the three sites: Punta Pescadero (PP), Canal de Ballenas (CB), and Isla Tiburon (IT). Gray hatching indicates no data were available. (Original data set, prior to pooling).

whale northern movement from the Costa Rica Dome breeding area to the northern feeding areas; however, our early detections in November and the findings of high calling rates over a 5 mo period contradict their suggestion. Song dominance, associated with reproductive behavior (McDonald *et al.* 2001, Oleson *et al.* 2007*a*), was found in all sites during early winter, which is consistent with a winter-breeding ground and suggests mating might be more frequent during these months. In contrast, D calls, associated with feeding behaviors (Oleson *et al.* 2007*a*), were registered from December, increasing at each site as the season progressed, and became dominant during spring. This finding fits in the seasonal pattern observed off California, where D calls are registered also in spring continuing during summer, shifting to songs and singular calls in summer and autumn (Oleson *et al.* 2007*b*). Therefore, a clear continuous seasonal acoustic pattern between the California feeding ground and the Gulf of California breeding area emerges and complement the vocal scenario for the northeastern Pacific blue whale population.

Blue Whale Calling Context

Songs and AB singular calls occurred during the same period in the Gulf of California, coinciding with previous reports off California (Oleson *et al.* 2007*b*), however, in the Gulf of California, less AB singular calls than songs were found at the beginning, reaching similar or higher proportion as the season progressed. These findings suggest that both songs and AB singular calls might have a reproductive context, but are used during different activities and may be intended for receiving animals at different distance ranges. Songs for instance, are used by some mysticetes for communication over long distances (Payne and Webb 1971, Clark and Ellison 2004, Oleson *et al.* 2007*b*), and are incompatible with feeding dives due to an insufficient volume of air at depths where feeding typically occurs (Aroyan *et al.* 2000). A significant volume of air is required for long sequences of A and B calls that are part of a blue whale song (Oleson *et al.* 2007*b*) and were found to be produced by males (Oleson *et al.* 2007*a*). In contrast, singular A and B calls, commonly recorded from pairs and group of individuals, are also produced by males, but while exhibiting different behaviors, such as feeding, milling, resting, or traveling, and are probably used for short range communication (Oleson *et al.* 2007*a*), including periods between deep foraging dives (Thode *et al.* 2000, McDonald *et al.* 2001, Oleson *et al.* 2007*a*). Thus A and B calls could be produced during feeding activity along with the D calls. On the other hand, D calls are produced by solitary individuals and groups of both sexes (Thode *et al.* 2000, McDonald *et al.* 2001, Oleson *et al.* 2007*a*). In this regard, the short duration and lower intensity of D calls produced by both sexes compared to AB singular calls, as well as their different seasonality within the Gulf of California and California, suggest that the D calls are related to social interaction or contact with conspecifics, while AB singular calls are linked to a reproductive context, but associated with feeding activities, when songs are not easily produced.

Blue Whale Call Seasonality and Trends per Site

Based on the calling peaks, we hypothesize that once the whales off the Canadian and U.S. coasts reach the southern part of the Gulf of California in November, they generally move to the northern region of the Gulf of California. The patterns of calls found in the northern region, suggest a movement between both northern regions as the season advances, however, these patterns could also be due to whales arriving at the northern regions at different times in consecutive years. Data collected from simultaneous recordings at these two sites would help to understand better which of these two hypotheses is more probable. Calling patterns showed that by March, the majority of whales have left the northern regions, and are probably back in the southwestern region of the Gulf of California. These findings agree with other data available, since this area has been studied intensively since 1993, particularly during February and March (Gendron and Ugalde de la Cruz 2012). However, there was a peak of D calls at IT in July 2007. This coincided with an unusual peak of blue whales at Bahia La Paz, in the southern region of the Gulf of California that was associated with the persistence of local pulses of biological production, related to krill aggregation (Pardo *et al*. 2013). Individuals remaining at IT could be associated with this unusual productivity pulse, however, further studies are needed to corroborate this hypothesis. In April there is another peak, but this time of D calls in the southern region of PP, matching the sightings of large groups of blue whale feeding at the entrance of the Gulf of California during this month (Gendron 2002).

The highest call rate (up to 37 detections per day) was found in the northern regions, suggesting that blue whales use this region more intensively than previously thought. Although passive acoustic monitoring does not allow us yet to infer blue whale abundance, this region shows a high primary productivity all year long due to wind-driven coastal upwelling and strong tidal currents, which cause extensive vertical mixing, providing the lowest sea surface temperatures and highest nitrate and silicate surface concentrations in the Gulf of California (Álvarez-Borrego 1983, Álvarez-Borrego and Lara-Lara 1991). CB, in the northern region, is also important for fin whales (*Balaenoptera physalus*), which are observed year-round (Ladrón-de-Guevara *et al*. 2015), and it may serve as a refuge of high productivity and prey abundance for cetaceans and seabirds during anomalous events, such as the strong El Niño-Southern Oscillation (ENSO) of 1982–1983 (Tershy *et al*. 1991). This region of potentially high prey availability for blue whales may result in a combination of feeding and singing behaviors, which is supported by several studies that have shown a link between prey availability and calls of blue and fin whales (Croll *et al*. 2002, Clark and Gagnon 2004, Stafford *et al*. 2005, Wiggins *et al*. 2005).

In the southern region of PP, however, call rates were lower (up to of 12 detections per day) and there was a clear shift from songs and AB singular to D call dominance as the winter/breeding season progressed. This suggests that blue whales produce songs at the beginning of the season, denoting the reproductive role of this type of call, although feeding is also observed frequently (Gendron 1992, 2002). We expect that pair bonds created previously are maintained during feeding *via* the production of AB singular calls, as Oleson *et al*. (2007*b*) proposed. In contrast, a shift to D calls at the end of the season, suggests that the region offshore of PP (in the middle of the Gulf of California entrance) may serve as an important feeding site before blue whales initiate their migration out of the Gulf of California, as proposed by Gendron (2002).

Final Remarks

This study uses data from a single recorder that was moved between three sites within the Gulf of California; therefore, we do not have simultaneous data at the three sites. During the study period (2005–2010), however, there were no anomalous environmental events, such as ENSO, that would have been a significant factor of variability; hence, months from different years were pooled to complete the time series and monthly data per site. However, we do not rule out that some extrinsic (*e.g.*, temperature) or intrinsic (*e.g.*, density of blue whales) environmental factors among years could affect our results to a certain degree.

Long-term acoustic monitoring of blue whales provides insights on seasonal and some behavioral patterns, mainly in areas where observation effort is low. While ongoing analysis, such as diel pattern of calls and relationship with environmental variables, will help to test our hypotheses further, acoustic data for blue whales from other regions in the Gulf of California are required for a better understanding of this winter/breeding habitat.

This is the first blue whale acoustic study based on the entire blue whale repertoire (including D calls) at a known winter-breeding ground (Gendron 2002). The results provide better understanding of the species' seasonality in the Gulf of California, particularly in the northern region (IT and CB), where sparse information on seasonality was known. The findings also complement the vocal scenario of the northeastern Pacific population.

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