Vol. 23: 241–252, 2014
doi: 10.3354/esr00566

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published online March 24

A new song recorded from blue whales in the Corcovado Gulf, Southern Chile, and an acoustic link to the Eastern Tropical Pacific

Susannah J. Buchan[1,2,3,*], Rodrigo Hucke-Gaete[3,4], Luke Rendell[5], Kathleen M. Stafford[6]

[1]Department of Oceanography, and [2]Center for Oceanographic Research in the eastern South Pacific, Universidad de Concepción, Barrio Universitario s/n, Concepción, Región del Bio Bio, Chile
[3]Centro Ballena Azul NGO, Casilla 567, Campus isla Teja, Valdivia, Chile
[4]Instituto de Ciencias Marinas y Limnológicas, Universidad Austral de Chile, Valdivia, Chile
[5]Sea Mammal Research Unit, Scottish Oceans Institute, School of Biology, University of St. Andrews, Fife KY16 8LB, UK
[6]Applied Physics Laboratory, University of Washington, Seattle, Washington 98105, USA

ABSTRACT: The identity, distribution and movements of blue whales *Balaenoptera musculus* that forage in the Chiloense Ecoregion in Southern Chile remain unclear. Studies of blue whale songs have identified acoustic populations with distinct song types, geographic ranges, migration routes and seasonal residencies — information that is relevant to the conservation of this endangered species. Here, we characterized the song sequences of blue whales that use the Corcovado Gulf based on dipping hydrophone recordings from 3 austral summer field seasons (2008, 2009, 2011), and compare these data to previously described song types for the Southeast Pacific (SEP) in order to better understand meso-scale (versus basin-scale) variation in blue whale song. Two distinct songs, SEP1 and SEP2, emerged from our analysis. Neither of these songs is used by Antarctic blue whales. Although SEP1 was the first song recorded in the Corcovado Gulf area in 1970, we found SEP2 to be the more common song, despite never having been reported previously in this area. Our report of SEP2 adds a new song to the current description of the SEP blue whale repertoire. Our recording of SEP1 reaffirms the acoustic link already established between Chile and the Eastern Tropical Pacific (ETP); our recording of SEP2 establishes a new acoustic link for this song between Chile and the ETP. These findings provide the basis for future passive acoustic studies on the temporal and spatial distributions of endangered SEP blue whales and for understanding how these songs relate to the population structure.

KEY WORDS: Chile · Southeast Pacific · *Balaenoptera musculus* · Whale song · Bioacoustics

INTRODUCTION

Blue whales *Balaenoptera musculus* were hunted to near extinction during the twentieth century, and although the species was protected internationally in 1966, illegal whaling continued into the early 1970s (Branch et al. 2004). In the Southeast Pacific (SEP), most blue whale catches occurred off the coast of Chile, but also off Peru and Ecuador (Clarke et al. 1978, Ramírez 1983, Van Waerebeek et al. 1997). Commercial whalers caught approximately 3000 blue whales off the coast of Chile between 1927 and 1971 (Aguayo-Lobo et al. 1998). In 2003, a blue whale feeding ground was discovered off the Pacific coast of Chiloé Island, the Corcovado Gulf and the Guaitecas Archipelago (Hucke-Gaete et al. 2004), and was subsequently found to extend farther north of Chiloé Island (Cabrera et al. 2005, Galletti Vernaz-

*Corresponding author: sbuchan@udec.cl

zani et al. 2012) and inshore, to the Inner Sea of Chiloé Island (Abramson & Gibbons 2010), thus spanning what is known as the Chiloense Ecoregion (Spalding et al. 2007). These reports indicate that this area could be important for the recovery of endangered SEP blue whales (Hucke-Gaete et al. 2004, Branch et al. 2007b). In December 1997, based on line-transect surveys following distance sampling protocols, an abundance estimate of 303 animals (95% CI: 176–625) was obtained for the exclusive economic zone waters off Chile between north (18° S) and central (38° S) Chile (Williams et al. 2011), excluding the more coastal waters of the Chiloense Ecoregion (within the 20 nautical mile limit).

In the Southern Hemisphere, 2 subspecies of blue whales are recognized, viz. the Antarctic blue whale *Balaenoptera musculus intermedia* and the pygmy blue whale *B. m. brevicauda*, although acoustic data suggest there may be at least 5 acoustically distinct populations (Stafford et al. 1999b, 2011, Širović et al. 2004, Samaran et al. 2013). There has been some confusion as to the type of blue whales present in the waters off the coast of Chile. Aguayo (1974) reported blue whales caught in Chilean waters as being either Antarctic or pygmy, while Clarke et al. (1978) proposed the Chilean blue whales to be a separate subspecies. More recently, Branch et al. (2007a) determined that the total lengths of blue whales were intermediate in size between the larger Antarctic blue whale and the smaller pygmy blue whale, suggesting that these were not only a separate population but also a unique unnamed subspecies. This is also supported by discrete summer distribution from Antarctic blue whales (Branch et al. 2007b), genetic analyses (Conway 2005, LeDuc et al. 2007) and a distinct acoustic repertoire (Cummings & Thompson 1971, Buchan et al. 2010). For management purposes, Chilean blue whales are considered a separate population from both Antarctic blue whales and Indian Ocean pygmy blue whales by the International Whaling Commission (www.iwc.int). Key questions thus remain regarding the identity, distribution and movements of this unnamed group of blue whales.

Blue whale vocalizations lend themselves particularly well to distinguishing among different populations of blue whales worldwide (e.g. Stafford et al. 1999b, 2001, McDonald et al. 2006). These sounds are some of the loudest sustained biological sounds in the ocean, capable of propagating over extremely long distances (Stafford et al. 1998, Širović et al. 2007). The biological function of many of these sounds remains unknown. Some appear to be used during feeding (D calls), while the patterned sequence of calls known as a 'song' has been attributed to male reproductive display, often produced during transit (Oleson et al. 2007). This patterned song sequence is made up of individual sounds or 'units' which occur in repeated 'phrases'. Blue whale song types have been characterized based on differences in some or all of the following criteria, most often determined by visual inspection of spectrograms: (1) song phrasing (e.g. ABABAB or ABCABC, where A, B and C represent different song units); (2) the inter-unit time interval; (3) total song phrase duration; and (4) song unit characteristics (frequency, duration, modulation) (e.g. Cummings & Thompson 1971, Thompson et al. 1996, Stafford et al. 1999b, McDonald et al. 2006).

Studies of blue whale song in particular have identified populations with distinct song types, geographic ranges, migration routes and seasonal residencies (e.g. Stafford et al. 1999a, 2001, 2011, McDonald et al. 2006, Samaran et al. 2013). Song characteristics are believed to remain relatively stable over a 40 yr period, and individual variability within song types is found to be minimal relative to the variation among song types (McDonald et al. 2006). Thus, song types may reflect recent distribution changes that are relevant to the conservation management of the various subspecies and populations of this endangered species. This is particularly useful in areas where different populations overlap, such as the North Pacific (Stafford et al. 2001), the Eastern Tropical Pacific (Stafford et al. 1999b) and the Indian Ocean (Stafford et al. 2011, Samaran et al. 2013).

Individuals from a single population of blue whales have been observed to produce variants of 1 basic song type (e.g. Stafford et al. 2001, Oleson et al. 2007), but have never been observed to produce more than 1 distinct song type. Variants have been described as being largely composed of the same units that define a given song type but in different proportions and temporal sequences, e.g. ABABAB versus ABBB. In the case of variants, the types of units and the order in which they occur remain stable over time. In contrast, a distinct song type consists of entirely different units, as characterized by peak frequency, duration and modulation characteristics. Proper characterization and classification of song types is essential prior to looking at patterns of overlap of song types in space and time that may reflect the seasonal passage of different whale populations through a given habitat (e.g. Stafford et al. 1999b, 2001, Samaran et al. 2010, 2013).

In the Chiloense Ecoregion of the SEP, only 1 song type has been reported (Cummings & Thompson 1971), which was the first ever documented recording of blue whale sounds obtained on 30 and 31 May 1970 near Guafo Island (Cummings & Thompson 1971), at the entrance to the Corcovado Gulf (Fig. 1). This song (see Fig. 2a) consisted of a 3-unit song, with A-B-C phrasing lasting a total of 36.5 s, with a 0.5 to 1.0 s pulse around 390 Hz described as a precursor to unit C. No further recordings were made of this song type until 1996 from a fixed hydrophone in the Eastern Tropical Pacific (ETP), at 8° S, 95° W (Stafford et al. 1999b). This SEP song was recorded in the ETP with greatest frequency during the austral winter (June to August). It was recorded along with a second song (see Fig. 2b) which followed the same temporal pattern, but had not been previously recorded elsewhere. This second song was considered a variant ('variant 2') of the first SEP song because both songs had similar phrasing and durations (Stafford et al. 1999b). Both songs were attributed to South Pacific blue whales.

Since the work in the 1970s, only 1 preliminary description of blue whale sounds from the Corcovado Gulf has been reported (Buchan et al. 2010). Buchan et al. (2010) made a coarse classification of the Chilean blue whale repertoire (isolated calls and song units), grouping all low-frequency long calls (>100 Hz, average duration 10 s) together and highlighting the presence of high-frequency short call precursors (approximate duration 1 s) at 350 and 420 Hz. These authors did not attempt song sequence characterization. Here, we analysed the data from Buchan et al. (2010) plus 2 additional years of data, and report a quantitative comparison of the specific song type characteristics recorded in the Corcovado Gulf.

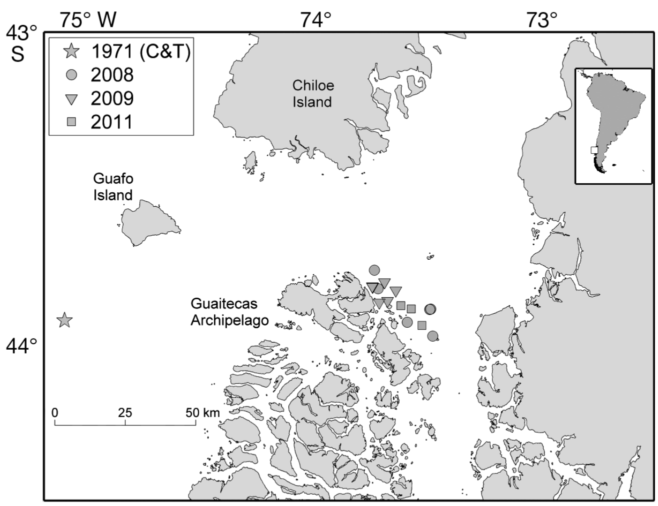

Fig. 1. Corcovado Gulf study area. Circles (2008), triangles (2009) and squares (2011) mark dipping hydrophone recording sites per year, and the star (labelled C & T) marks the recording location from Cummings & Thompson (1971)

In this study, our objective was to characterize the song of the blue whales that forage in the Corcovado Gulf during the austral summer months (February to April) based on dipping hydrophone recordings from 3 field seasons (2008, 2009 and 2011), and compare them to the 2 previously described song types/variants for the SEP by Cummings & Thompson (1971) and from the ETP by Stafford et al. (1999b), in order to better understand meso-scale (versus basin-scale) differences in blue whale songs within the SEP.

MATERIALS AND METHODS

Acoustic data collection

During the austral summers of 2008 (February to April; Buchan et al. 2010), 2009 (February to March) and 2011 (March), we conducted acoustic monitoring in our study area (1542 km^2 total) located in the coastal waters of the Guaitecas Archipelago and the Corcovado Gulf, Chile (43° 54′ S, 73° 44′ W; Fig. 1). Data were collected from an 8 m outboard-powered vessel. Blue whales were located with aid of land-based observers working with binoculars and a theodolite for tracking. Whales were identified visually from the vessel with binoculars and the naked eye, first by identifying their blow and then by confirming species upon closer approach.

Recording equipment and settings were selected in order to ensure that sufficient energy was captured at frequencies necessary to characterize song units (20–400 Hz) but also to diminish background noise at low frequencies. Nevertheless, high levels of low-frequency background noise were present. Hydrophone recordings were made in 2008 and 2009 with an omni-directional hydrophone (Cetacean Research Technology C54XRS) with a flat frequency response from 0.016 to 44 kHz (+2/−3 dB) and a usable frequency response of 0.006 to 203 kHz (+2/−20 dB), a digital high-pass filter set at 20 Hz (Cetacean Research Technology), an Edirol 96-bit USB sound card sampling at 96 kHz and a Panasonic Toughbook laptop computer with Raven Pro 1.3 recording software (Bioacoustics Research Program 2008). In 2011, single hydrophone recordings were made with an SQ26-MT portable underwater recording system (Cetacean Research Technology), which includes an omni-directional hydrophone with a flat frequency response from 0.020 to 20 kHz (+2/−2 dB) and a usable frequency response of 0.01 to 50 kHz (+2/ −15 dB), and an M-Audio Microtrack recorder sampling at 96 kHz. Recording effort was carried out regardless of whether blue whales were in sight, but not in the presence of other cetaceans. All sightings (number of groups, number of individuals, approximate distance estimated visually) were noted.

Whale song characterization: phrases and units

A blue whale song sequence is composed of several repeated phrases. Each phrase is a patterned sequence of song units and shorter 'unit-precursor' sounds. Spectrograms of complete song phrases, with labelled song units and unit precursors, are presented (see Fig. 3). Songs were characterized from visual inspection of spectrograms between 0 and 500 Hz, using the following criteria: (1) song phrasing; (2) the inter-unit gaps between song units; (3) total song phrase duration; and (4) song unit characteristics (frequency, duration, modulation) (Cummings & Thompson 1971, Stafford et al. 1999b, Mellinger & Clark 2003). Within a song sequence, each unique unit within the repeated phrases was named according to its order of appearance in the phrase, e.g. A for the first unit, B for the second, C for the third (Cummings & Thompson 1971). In the literature, this method of labelling song units does not imply that, for example, unit A from the North Pacific song is identical to unit A from the Indian Ocean song; it merely expresses the position of the unit in the song phrase. However, in order to avoid this confusion, we additionally annotated units according to the song they belonged to, based on our classification of song. Thus, song units and phrases were described as A1-B1-C1 for the first song type, A2-B2-C2 for the second, and so on, to emphasize the song that units belonged to. Unit precursors were labelled according to the unit they preceded (pre-A1, pre-B1, pre-C1 etc.). The time (s) between 2 consecutive units (or between a unit and the precursor to the following unit) defined the inter-unit gap. Total song phrase duration was determined by the time between the start of the first unit and the end of the last unit; the last unit in the phrase was easily distinguishable since it was followed by a much longer time gap (>50 s) before the start of a new phrase. Song units were considered to be delimited by an abrupt change in the frequency or modulation rate, irrespective of a pause between song units (McDonald et al. 2006), and each unit was characterized by measuring its peak frequency (Hz) and duration (s), and assigned modulation characteristics (pulsed or tonal, where possible; Cummings & Thompson 1971).

Spectrogram analysis of whale songs

Recordings were analysed in spectrograms and waveform plots created in Raven Pro 1.3 (Hamming window; 90% overlap; window size 60 000 samples; Fast Fourier Transform (FFT) 65 536 samples, Bioacoustics Research Program 2008). All spectrograms were scanned visually for blue whale calls within the 0 to 500 Hz frequency range, and only blue whale song units and phrases were analysed. Blue whale song units and unit-precursors were selected manually on-screen using a cursor and committed to selection tables that compiled the following data for each selection: begin time (s), end time (s), low frequency (Hz), high frequency (Hz), peak frequency (Hz; the frequency at which peak power occurs), unit amplitude modulation (where signal-to-noise ratio was sufficient, modulation rate of pulsed sounds was determined as the number of pulses per second) and unit type (e.g. A1, B2).

Following the compilation of selection tables in Raven Pro 1.3 (Bioacoustics Research Program 2008), we calculated the duration of units (end time minus begin time in seconds), the average inter-unit interval for each set of consecutive units (time between the end of one unit and the beginning of the following unit, in seconds) and the average inter-phrase interval (from the beginning of one phrase to the beginning of the following phrase in seconds).

The final set of song characteristics determined from the data for song sequence characterization were (1) peak frequency of song units and unit precursors, (2) duration of song units and unit precursors, (3) duration of inter-unit gaps and (3) duration of total phrase.

Whale song comparison

Once blue whale song sequences were visually inspected and quantitatively characterized, they were compared to song descriptions by Cummings & Thompson (1971) from the Corcovado Gulf and Stafford et al. (1999b) for the ETP. In order to visually compare our song sequences with both of these previous studies, we decimated our data to a 100 Hz sample rate (see Fig. 2). Sounds from Cummings & Thompson (1971) were recorded with a hydrophone with a pre-amplifier (Wilcoxon, type M-H90-A) suspended ~28 m below a ~305 m (1000 ft) floating cable, with a low-frequency response of 3 dB at 12 Hz; sounds were recorded on a battery-powered magnetic tape recorder. A digital copy of the song sequence recorded by Cummings & Thompson (1971) was obtained from the Macaulay Library at Cornell University, USA, which we decimated to 100 Hz sample rate. Sounds from Stafford et al. (1999b) were recorded with an autonomous hydrophone logging system with an International Corporation 1032 hydrophone, preamplifier/filter (designed to prewhiten ocean ambient noise spectra from 1 to 40 Hz) and a digital recorder in a pressure resistant titanium housing. The hydrophone was suspended in the deep sound channel at depths of 650 to 750 m and set to record up to 6 mo at a sampling rate of 100 Hz with low pass filters set at 40 Hz. The methods employed in both of these studies make the data largely comparable with data from this study, although our signal-to-noise ratio (SNR) is somewhat poorer.

RESULTS

Sampling effort and context

In total, 29 h and 11 min were recorded during the austral summers in February to April 2008, February to March 2009 and March 2011 (Table 1) within the Corcovado Gulf study area. Song recordings coincided with sightings of groups of 1 to 3 blue whales first sighted at an observed distance of 500 m to 2 nautical miles of the research vessel. The distance to the source of sounds was not measured; therefore, it is possible that sounds recorded may have been produced by whales farther away than those animals sighted near the vessel. We selected a total of 345 units within 67 song phrases for analysis, excluding 157 sounds that were isolated calls (not clearly part of a song sequence) and song units/phrases with an SNR considered to be too poor to distinguish the start and end of each unit.

Table 1. *Balaenoptera musculus*. Total acoustic monitoring effort in hours, number of separate days when songs were recorded, total song units (including unit precursor sounds) and total song phrases of Southeast Pacific (SEP) blue whale song types SEP1 and SEP2, recorded during the austral summers of 2008, 2009 and 2011 in the Corcovado Gulf blue whale feeding ground

	2008 (Feb–Apr)	2009 (Feb–Mar)	2011 (Mar)	All years
Total hours:minutes of effort	16:03	10:46	2:49	29:11
Total days when songs were recorded	5	3	2	10
Total SEP1 song units	18	0	0	18
Total SEP2 song units	117	187	41	345
Total SEP1 song phrases	5	0	0	5
Total SEP2 song phrases	22	32	8	62

Description of the two SEP songs

Based on the frequency characteristics of song units and unit precursors (Table 2), and the temporal characteristics of song phrases and units (Table 3), we distinguished 2 different songs, which we named SEP1 (Southeast Pacific 1; Figs. 2a,c & 3a) and SEP2 (Southeast Pacific 2; Figs. 2b,d & 3b).

SEP1 (Figs. 2c & 3a; Tables 2 & 3) was only recorded during a single song sequence on 23 February 2008, and only 5 phrases were recorded; on that day no other song sequence was recorded. This small sample size is a clear limitation to the characterization of this song sequence. This song consisted of 3-unit phrases (A1-B1-C1) that each lasted on average 33.9 s. The first unit (A1) had a mean peak frequency of 21 Hz and an average duration of 11.4 s. It was followed immediately by unit B1 with mean peak frequency of 49 Hz and average duration of 9.2 s. Unit C1 had a mean peak frequency of 25 Hz and lasted 9.5 s and was almost always (4 times out of 5) preceded by a short (0.7 s), high-frequency pulse (350 Hz) that we named precursor-C (pre-C1; circled in Fig. 3a).

SEP2 (Figs. 2d & 3b; Tables 2 & 3) was recorded during all 3 field seasons (2008, 2009, 2011), totalling 62 phrases.

Table 2. *Balaenoptera musculus*. Frequency characteristics of Southeast Pacific (SEP) blue whale song types SEP1 and SEP2: mean peak frequencies (rounded to nearest whole number) ± SD (rounded to nearest decimal) of unit precursors (Pre-A, Pre-C, Pre-D) and song units (A–E); sample sizes are in parentheses. Peak frequency refers to the frequency at which peak power (amplitude) occurs within the selected sound; NA: not applicable

	Mean peak frequency (Hz)							
	Pre-A	Unit A	Unit B	Pre-C	Unit C	Pre-D	Unit D	Unit E
SEP1	NA	21 ± 0.8 (4)	49 ± 17.1 (5)	350 ± 3.3 (4)	25 ± 0.0 (5)	NA	NA	NA
SEP2	414 ± 15.5 (48)	55 ± 12.1 (57)	84 ± 7.6 (62)	NA	35 ± 16.6 (61)	356 ± 9.7 (53)	37 ± 17.3 (60)	85.3 ± 2.2 (4)

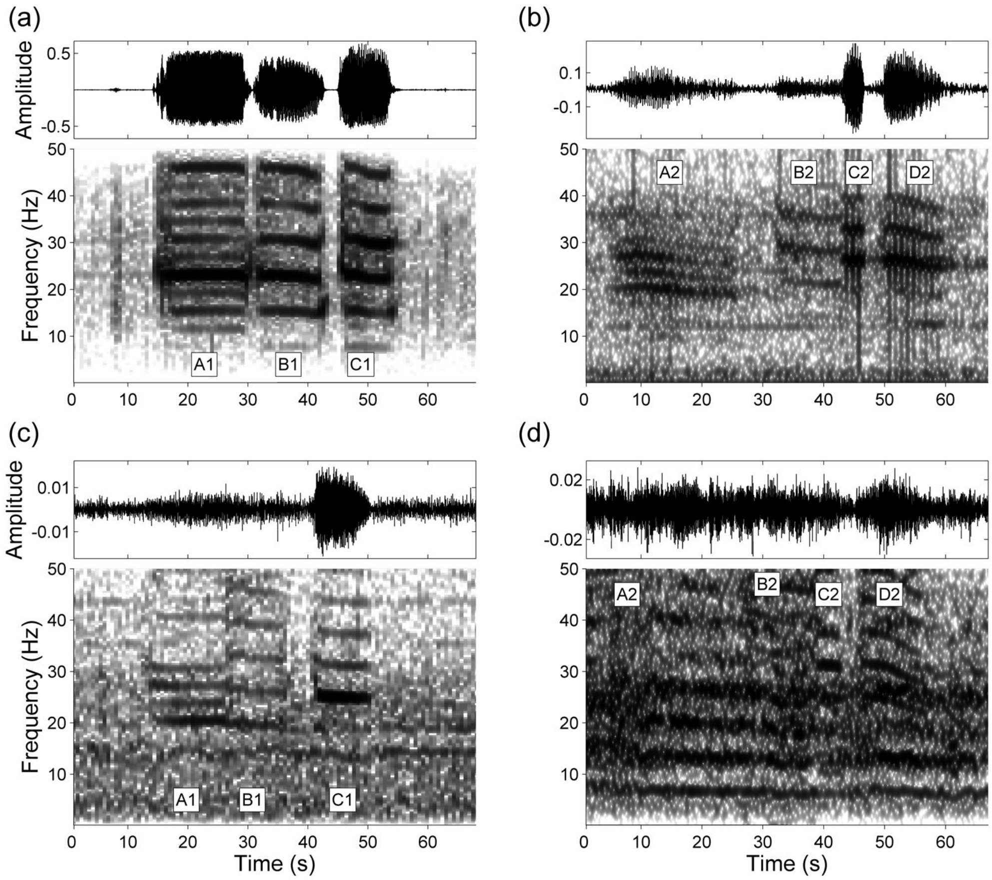

Fig. 2. *Balaenoptera musculus.* Waveforms (top panels) and spectrograms (bottom panels), of blue whale songs: (a) SEP1 from Cummings & Thompson (1971) obtained from the Macaulay Library (http://macaulaylibrary.org/) downsampled to 100 Hz; (b) SEP2 from Stafford et al. (1999b) sampled at 100 Hz; (c) SEP1 from this study downsampled to 100 Hz; (d) SEP2 from this study downsampled to 100 Hz. Song units are marked by A, B, C, D with song type 1 or 2 annotations. Unit precursors are not shown. Spectrogram parameters for (a) and (c) are FFT: 256, 128-point Hanning window, 50% overlap; for (b) and (d), FFT: 1024, 128-point Hanning window, 90% overlap. Note that (d) is poorly visualized due to high low-frequency background noise; Fig. 3 shows 0–500 Hz bandwidth spectrograms of sounds (c) and (d)

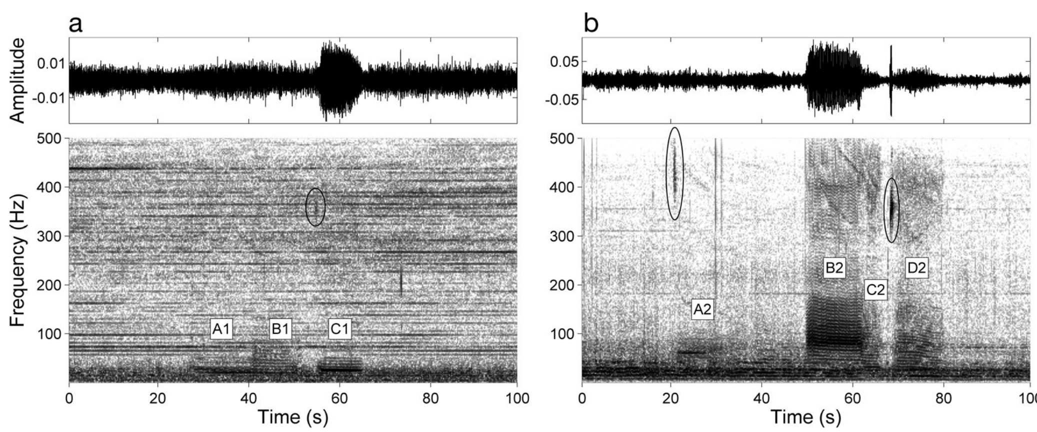

Fig. 3. *Balaenoptera musculus.* Waveforms (top panels) and spectrograms (bottom panels) of blue whale songs from this study downsampled to 1 kHz: (a) SEP1, (b) SEP2. Spectrogram parameters are FFT: 1024, 512-point Hanning window, 50% overlap. Song units are marked by A, B, C, D with annotations 1 for SEP1, and 2 for SEP2, and circles indicate short duration higher frequency unit precursors (pre-C1 for SEP1; pre-A2 and pre-D2 for SEP2)

Table 3. *Balaenoptera musculus.* Temporal characteristics of Southeast Pacific (SEP) blue whale song types SEP1 and SEP2, from Cummings & Thompson (1971), Stafford et al. (1999b) and this study: mean duration (s) ± SD (sample size in parentheses) of unit precursors (pre-A, pre-C, pre-D), song units (A–E), inter-unit gaps (A-B, B-C, C-D, D-E), total song from start to end and song interval, measured from the start of a song to the start of the following song. NA: not applicable; –: no available data

Song type and source	Pre-A	Unit A	Gap A-B	Unit B	Gap B-C	Pre-C	Unit C	Gap C-D	Pre-D	Unit D	Gap D-E	Unit E	Total phrase	Inter-phrase interval
SEP1: this study	NA	11.4±2.7 (4)	0.07±0.1 (4)	9.2±0.5 (5)	5.0±0.8 (5)	0.7±0.1 (4)	9.5±0.4 (5)	NA	NA	NA	NA	NA	33.9±5.6 (5)	107.9±31.7 (3)
SEP1: Cummings & Thompson (1971)	NA	13.4[a] 15.3[b]	0[a] 1.6[b]	10.3[a] 9.6[b]	2.5[a] 3.7[b]	0.5–1.0	9.0[a] 7.9[b]	NA	NA	NA	NA	NA	36.9[a] 36.2[b]	100[a] 106[b]
SEP1: Stafford et al. (1999b)	NA	13.4±1.1 (25)	–	9.1±1.2 (25)	–	–	8.4±0.5 (25)	NA	NA	NA	NA	NA	38.8±1.8 (25)	–
SEP2: this study	0.7±0.1 (48)	9.5±6.9 (57)	19.5±1.7 (50)	12.6±0.4 (62)	0.3±0.3 (53)	NA	4.5±0.8 (61)	2.2±0.7 (52)	1.0±0.2 (53)	8.0±2.7 (60)	10.8±6.9 (4)	12.6±0.1 (62)	59.6±6.7 (62)	222.9±344.7 (46)
SEP2: Stafford et al. (1999b)	–	17.7±3.8 (23)	–	10.8±0.6 (9)	–	–	4.0±0 .5 (23)	–	–	10.8±1.5 (23)	–	–	53.5 NA	–

[a]Whale 1 and [b]Whale 2 from Cummings & Thompson (1971)

This song generally consisted of a 4-unit phrase (A2-B2-C2-D2; n = 58) lasting on average 60 s, with an additional unit E2 in 4 phrases from a single song sequence recorded in 2009. Unit A2 had a peak frequency of 55 Hz and an average duration of 9.5 s, and was almost always preceded by short (0.7 s) high-frequency pulse (414 Hz) that we named pre-A2 (circled in Fig. 3b). After an average inter-unit gap of 19.5 s, unit A2 was followed by unit B2, which had a mean maximum frequency of 84 Hz and a mean duration of 12.6 s. Unit B2 was strongly amplitude modulated, similar to B1 in SEP1, and where the SNR was sufficient (n = 10), a modulation rate of 6.62 s^{-1} ± 0.11 SD was determined (equal to an inter-pulse interval = 0.15 s). Unit C2 had a mean maximum frequency of 35 Hz and a mean duration of 4.5 s. Unit D2 had a mean maximum frequency of 37 Hz and a mean duration of 8.0 s, and was almost always preceded by a short (1 s) high-frequency (356 Hz) precursor that we named pre-D2 (circled in Fig. 3b). An additional unit E2 was recorded 4 times during 1 song sequence, with a mean maximum frequency of 37 Hz and a mean duration of 12.6 s.

Comparison between SEP songs

To graphically explore how similar or distinct the song units and unit precursors of both songs are, we plotted the peak frequencies and durations of all units and precursors (Fig. 4a,b, respectively). Given our relatively small sample size, no statistics were applied. Most units were distinct from one another; however, a high degree of similarity was clear between SEP1 unit B (B1) and SEP2 unit A (A2), as well as between SEP1 precursor C (pre-C1) and SEP2 precursor D (pre-D2). Unit B and unit E of SEP2 also appeared to be quite similar.

Higher bandwidth spectrogram examples of SEP1 and SEP2 are given in Fig. 3a and b, respectively, which show higher SNR compared to lower bandwidth spectrograms, given the high levels of low-frequency noise. Visual inspection of these spectrograms, as well as data in Tables 2 & 3, reveal the following differences between SEP1 and SEP2: (1) different song phrasing (A1-B1-C1 versus A2-B2-C2-D2); (2) different inter-unit gap durations (for A-B and B-C gaps); (3) the occurrence of precursors to different song units (pre-C1 in SEP1; pre-A2 and pre-D2 in SEP2); (4) different frequency and duration characteristics of song units (A1 versus A2; B1 versus B2; C1 versus C2); (5) different phrase durations (34 s for SEP1 versus 59 s for SEP2).

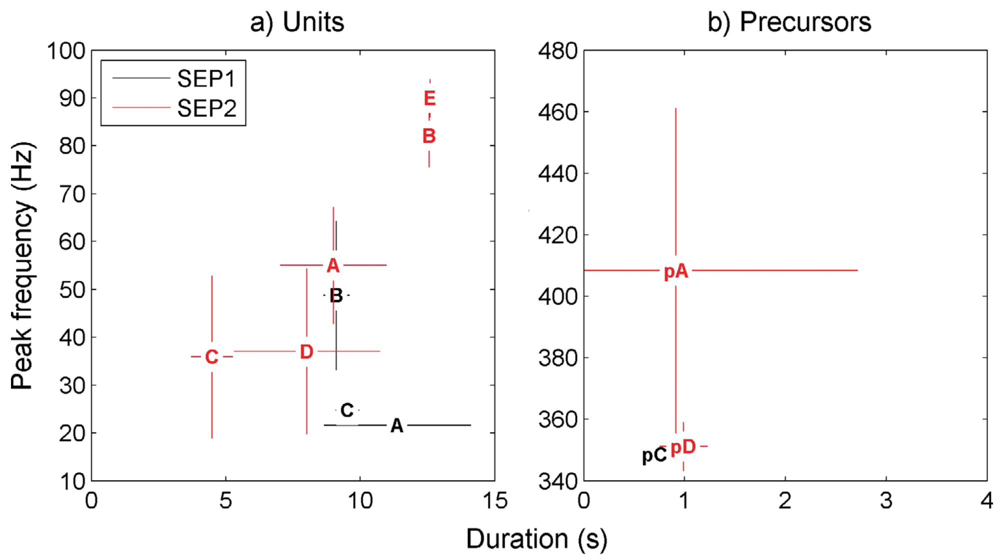

Fig. 4. *Balaenoptera musculus.* Plot of average peak frequency vs. duration of (a) blue whale song units and (b) unit precursors for SEP1 (in black) and SEP2 songs (in red). Bars indicate total range of values. Song units and unit precursors are marked as A, B, C, D, E. Unit precursors are marked as pA, pC and pD

Comparison of SEP songs with previous studies

In order to classify the SEP songs recorded here, we compared them to other blue whale songs described in the literature, in particular for the same study area by Cummings & Thompson (1971), and for the ETP by Stafford et al. (1999b). Overall, SEP1 and SEP2 phrases and individual units were more similar to each other than to any other blue whale song described for regions outside the SEP and the ETP; no song types currently attributed to blue whales in Antarctica (Širović et al. 2004) or elsewhere (e.g. McDonald et al. 2006) match the songs reported here.

When comparing our song measurements (Tables 2 & 3), and the spectrograms for SEP1 (Fig. 2c) and SEP2 (Fig. 2d), with the previously recorded songs by Cummings & Thompson (1971; Fig. 2a) and Stafford et al. (1999b; Fig. 2b), we found that SEP1 matched with the song described by Cummings & Thompson (1971) for the Corcovado Gulf and also matched 'variant 1' in Stafford et al. (1999b) from the ETP. SEP2 matched 'variant 2' reported by Stafford et al. (1999b) from the ETP.

DISCUSSION

The proper characterization and classification of song type is essential given the implications of song type in defining acoustic groups of blue whales. This analysis is particularly relevant given the current availability of fixed passive acoustic technologies that provide long-term data sets. These can be used to examine patterns of song type overlap in space and time that may reflect the seasonal passage of different acoustic groups through the same habitat (e.g. Stafford et al. 1999a, 2001, 2011, Samaran et al. 2010, 2013).

Blue whale song types and variants

In the literature, a single population, or acoustic group, of blue whales has been known to produce phrasing variations of 1 basic song type (e.g. Stafford et al. 2001, Oleson et al. 2007), but not to produce more than 1 distinct song type (i.e. with a completely different set of units). Song type characteristics are believed to remain relatively stable over a 40 yr period (McDonald et al. 2006). A variant of a song type is a song made up of a majority of the same song units (with matching peak frequency, duration and modulation characteristics) but with different phrasing, e.g. A1-B1-A1-B1 and A1-B1-B1-B1. These kinds of variants can be observed in songs produced by blue whales in the Northeast Pacific (Stafford et al. 2001, Oleson et al. 2007). It remains unclear whether these variants are caused by individual or some other source of variation. Based on limited observations, individual variation has been documented within blue whale song types, although it appears to be minimal relative to the variation among song types (McDonald et al. 2006 and references therein).

The 2 song sequences (patterned phrases and individual units) presented here are much more similar to each other than they are to song types from other geographic locations, e.g. Antarctica (Širović et al. 2004). However, there are distinct differences between SEP1 and SEP2, which are also apparent. The SEP1 song phrase consists of only 3 units while the SEP2 song phrase is made up of 4 units; the SEP2 phrase is roughly twice as long as the SEP1 phrase; lastly, units in each song are largely distinct from one another in peak frequency and duration, with the exception of B1 being similar to A2 and pre-C1 similar to pre-D2. At this stage, given the small sample size, particularly in the case of SEP1 (n = 5), it is not possible to determine whether these 2 songs are variants of each other or are altogether different song types. However, a clearer case of a variant, possibly due to individual variation, is that of SEP2, with the inclusion of additional end unit E2 in only 4 phrases, while the other phrases only had units A to D. Thus, A2-B2-C2-D2 and A2-B2-C2-D2-E2 phrasing can be considered variants of the SEP2 song. Continuous data and greater sample sizes of song phrases will be needed to clarify this issue.

SEP blue whale song classification

The 1970 recording of a song sequence from 2 blue whales at the entrance of the Corcovado Gulf by Cummings & Thompson (1971) is the only description of the SEP blue whale song up until now and is considered the only characteristic song type for SEP blue whales in the literature (Stafford et al. 1999b, McDonald et al. 2006). This song was later recorded on a fixed hydrophone in the ETP (8° S 95° W) during March to August, the austral winter (Stafford et al. 1999b). These authors also recorded another song, which they classified as a variant ('variant 2') of the song recorded by Cummings & Thompson (1971). Here, based on our analysis of the frequency characteristics of song units and song unit precursors, and the temporal characteristics of song phrases and song units of the song sequences produced by blue whales that feed in the Corcovado Gulf, we distinguished 2 songs, which we named SEP1 and SEP2. This adds a new song to the repertoire of blue whales in Chile. Based on the detailed comparison of SEP1 and SEP2 with the previous songs recorded by Cummings & Thompson (1971) and Stafford et al. (1999b), we conclude that SEP1 is the same song reported by Cummings & Thompson (1971), and SEP2 is variant 2 reported by Stafford et al. (1999b).

The small sample size for SEP1 (n = 5) makes song sequence characterization based on this study alone problematic, but we believe that its similarity to reports by Cummings & Thompson (1971) and Stafford et al. (1999b), which both document its existence, supports the robustness of our classification. We recognize that the high levels of low-frequency noise in our recordings may have affected quantitative song unit measurements due to poor SNR. For some sounds, high noise levels at low bandwidths (0–25 Hz) meant that any potential peak frequency of units at these lower bandwidths could not be measured (e.g. SEP2 in Fig. 2d) or that the measurements of duration of less intense song units were highly variable, like unit A in SEP2 (Table 3). However, there is no reason to believe that these quantitative measurement errors were sufficiently consistent in magnitude or direction to systematically bias the results enough to render the obvious distinctions between the 2 songs spurious. Furthermore, it is the case that different sample rates could have affected comparisons with data described in previous studies. The Stafford et al. (1999b) data were sampled at a very low sample rate (100 Hz, versus 96 kHz in our study) such that the bandwidth was only 0.1 to 40 Hz and therefore many of the elements that help to characterize the 2 songs in our study were not recorded by those authors. We attempted to mitigate this by decimating our data and the data of Cummings & Thompson (1971) to a sample rate of 100 Hz for visual comparison (Fig. 2).

High-frequency song unit precursors

The occurrence of short (~1 s), higher frequency (>350 Hz) precursors to unit C1 in SEP1 and to units A2 and D2 in SEP2 (Fig. 3a,b), is noteworthy since they have seldom been reported in the literature and lie well above the frequency ranges generally reported for blue whales. These sounds may have been often overlooked in previous analyses or missed by low sampling rates. However, Cummings & Thompson (1971, p. 1195) did mention the occurrence of 'a 0.5- to 1-sec pulse of about 390 Hz' prior to the start of unit C1 in the SEP1 song; McDonald et al. (2001) also reported a high-frequency precursor to unit B in the blue whale song recorded off California. These precursors were useful in distinguishing between SEP1 and SEP2 in this study; we therefore recommend that sufficient sample rates (>1 kHz) be used and these sounds be reported in future blue whale song studies to enable more robust classification.

SEP2: a new song described for SEP blue whales

We describe 2 songs, SEP1 and SEP2, the latter of which was largely predominant with 62 phrases recorded compared with 5 phrases of SEP1. In the Chiloense Ecoregion, only SEP1 had been previously described (Cummings & Thompson 1971), so the present study is the first to describe the SEP2 song in the Chiloense Ecoregion. The song type was previously described as 'variant 2' in the ETP by Stafford et al. (1999b), who attributed it to southern blue whales based on its seasonality, i.e. higher call intensities during the austral winter. Our recording of SEP2 much farther south of the ETP confirms this interpretation. We propose that it be considered as part of the SEP blue whale repertoire for future acoustic studies in this region. These findings also suggest that most blue whales using the Corcovado Gulf feeding area in the austral summer use the SEP2 song and not the SEP1 song, although a longer data set will be necessary to confirm this.

An acoustic link between the ETP and the Chiloense Ecoregion

The occurrence of SEP1 and SEP2 in the Corcovado Gulf (Cummings & Thompson 1971, this study) and in the ETP (Stafford et al. 1999b) establishes an acoustic link between the Chiloense Ecoregion and the ETP, which suggests that the same group(s) of blue whales migrate between these 2 locations. Stafford et al. (1999b) recorded both songs in roughly equal proportions at a fixed hydrophone array in the ETP, at 8° S, 95° W, but rarely above the Equator. Both songs displayed a clear, similar, seasonal pattern: significantly more frequent calling between late January and the end of August, indicating that at least a proportion of SEP blue whales migrate south from the ETP during the austral summer. Unfortunately, the inherent limitations of our sampling method mean that it was not possible to determine the temporal and spatial distribution patterns of SEP songs. Satellite tagging data suggest that some proportion of the animals that feed in the Corcovado Gulf during the austral summer travel north to spend the winter in the ETP (Hucke-Gaete 2004). However, sighting data (Findlay et al. 1998), as well as some recent records (Abramson & Gibbons 2010, Försterra & Häussermann 2012), have documented the presence of blue whales in the Chiloense Ecoregion until the beginning of July. It is still unclear, therefore, whether some blue whales remain year-round in the Chiloense Ecoregion or whether some whales start to migrate out of the area later in the year, past the month of July. Until we have year-round acoustic data from fixed hydrophone systems and sighting data for the feeding sites in the Chiloense Ecoregion (e.g. Corral, Northeast Chiloe, Corcovado Gulf), it will be difficult to fill these knowledge gaps.

Blue whale acoustic groups

The overlap of distinct song types temporally and/or spatially is not uncommon in blue whales, and it is thought to reflect the seasonal passage of different acoustic populations through different areas. In the North Pacific, one song type has been recorded in the Northeast Pacific, and a different song in the Northwest Pacific, both with similar seasonal variations, but largely spatially distinct (Stafford et al. 2001). These songs overlap in space and time in the Gulf of Alaska (Stafford 2003), and both occur in the central North Pacific but not at the same time (Stafford et al. 2001). In the Indian Ocean, where multiple acoustic populations exist, the overall distribution of song types suggests that, although these acoustic populations have some limited overlap, they do mostly have distinct ranges (Alling et al. 1991, McCauley et al. 2000, Samaran et al. 2013). In some cases, where different song types overlap spatially, recorded at the same fixed location, they displayed largely different seasonalities and proportions of occurrence, as seen in the ETP where both Northeast Pacific and SEP blue whale songs have been recorded (Stafford et al. 1999b).

In this study, the possible occurrence of 2 song types, as opposed to 2 variants, in the Corcovado Gulf could indicate (1) the presence of 2 distinct blue whale acoustic groups that exploit this feeding area at similar times of year, but have different distributions (e.g. onshore or offshore), seasonal residencies and migration routes; or (2) the presence of one acoustic group with higher levels of song type variation than have been previously described for a single population of blue whales, for example due to individual variation or different behavioural contexts. In the ETP, both SEP1 and SEP2 were recorded with similar seasonality (austral winter) according to Stafford et al. (1999b), which suggests common migration and thus that both songs could stem from the same population. The similarities between the song units of SEP1 and SEP2 could suggest their evolution from a common stock source. Given the limited temporal and spatial coverage of our acoustic data, and the lack of integrated photo-identification and genetic data for these animals, it is unclear how these 2 songs reflect population structure.

CONCLUSIONS

These data from the austral summers of 2008, 2009 and 2011, which include the data reported by Buchan et al. (2010), are the first recordings of blue whales in the Chiloense Ecoregion of Southern Chile since 1970 (Cummings & Thompson 1971). Two distinct songs emerged from our analysis that should be used to monitor the temporal and spatial distribution of SEP blue whales in future passive acoustic studies. SEP1 matched the song described by Cummings & Thompson (1971) recorded at the entrance of the Corcovado Gulf, although we only recorded this song on 1 day throughout our 3-summer study period. The SEP2 song, on the other hand, was much more common, recorded on multiple days during all 3 summer seasons. Our report of SEP2 adds a new song to the current description of the SEP blue whale repertoire. Our findings suggest that most blue whales using the Corcovado Gulf feeding ground during the austral summer use the SEP2 song and not the SEP1 song. Both SEP1 and SEP2 songs were recorded by Stafford et al. (1999b) in the ETP. This acoustic link suggests a north–south migration of SEP blue whales between Chile and the ETP.

Given the importance of song type studies in defining acoustic groups of blue whales, by characterizing the songs of SEP blue whales, our findings open up questions for future passive acoustic research on SEP blue whales. Future studies should focus on the use of fixed passive acoustic techniques that provide greater spatial and temporal coverage in order to answer certain key questions: (1) Are these SEP songs sufficiently different to be classified as different song types or are they variants of each other? (2) How do SEP blue whale songs overlap in space and time within the Chiloense Ecoregion feeding ground and the wider SEP region? (3) How do these songs relate to SEP blue whale population structure? Answering these questions will bring us closer to resolving the issue of population identity, distribution and movements of endangered SEP blue whales. Moreover, whale song studies will need to be integrated with photo-identification, genetics studies and satellite tracking, due to likely mixing of groups in the Chiloense Ecoregion and the SEP.

Acknowledgements. We thank the staff of the local Chilean NGO Centro Ballena Azul (Blue Whale Centre) for their hard work during the field seasons and over the years and D. Caniullan of Puerto Melinka for excellent skippering. This study was funded by grants to S.J.B. from NGO One World Wildlife. S.J.B. was supported by the Centre for Oceanographic Research in the eastern South Pacific (COPAS-Sur Austral, Project PFB-31/2007) and the Postgraduate Office at the University of Concepción. This work was made possible by grants to R.H.G. from the Wildlife Conservation Society, Dirección de Investigación from Universidad Austral de Chile, Whale and Dolphin Conservation Society, AVINA Foundation, Oregon State University, Natural Resources Defense Council, World Wildlife Fund, Rufford Small Grants Foundation, Gobierno Regional de Los Lagos, Whitley Fund for Nature and gifts from N. and G. Duffield and also from S. and D. Rockefeller, through the long-term research programme 'Blue whale ecology and conservation in Chile'. L.R. received funding from the The Marine Alliance for Science and Technology (MASTS) pooling initiative, and their support is gratefully acknowledged. MASTS is funded by the Scottish Funding Council (grant reference HR09011) and contributing institutions. We thank the Macaulay Library at Cornell University for providing us with the original Cummings & Thompson (1971) recording. Lastly, our thanks go to the anonymous reviewers whose comments greatly helped improve this manuscript.

LITERATURE CITED

Abramson ZJ, Gibbons J (2010) New records of blue whales (*Balaenoptera musculus* Linnaeus, 1758) in winter season in the inlet waters of Chiloe – continental Chile. An Inst Patagonia 38:105–108

Aguayo A (1974) Baleen whales off continental Chile. In: Schevil WE (ed) The whale problem: a status report. Harvard University Press, Cambridge, MA, p 209–217

Aguayo-Lobo A, Torres D, Acevedo R (1998) Los mamíferos marinos de Chile: I. Cetacea. Ser Cient INACH 48: 19–159

Alling A, Dorseaynd EM, Gordon JCD (1991) Blue whales (*Balaenoptera musculus*) off the northeast coast of Sri Lanka: distribution, feeding and individual identification. UNEP Mar Mamm Tech Rep 3:247–258

Bioacoustics Research Program (2008) Raven Pro: interactive sound analysis software (Version 1.3). The Cornell Lab of Ornithology, Ithaca, NY. Available at www.birds.cornell.edu/raven

➤ Branch TA, Matsuoka K, Miyashita T (2004) Evidence for increases in Antarctic blue whales based on Bayesian modelling. Mar Mamm Sci 20:726–754

➤ Branch TA, Abubaker EMN, Mkango S, Butterworth DS (2007a) Separating southern blue whale subspecies based on length frequencies of sexually mature females. Mar Mamm Sci 23:803–833

➤ Branch TA, Stafford KM, Palacios DM, Allison C and others (2007b) Past and present distribution, densities and movements of blue whales *Balaenoptera musculus* in the Southern Hemisphere and northern Indian Ocean. Mammal Rev 37:116–175

➤ Buchan SJ, Rendell LE, Hucke-Gaete R (2010) Preliminary recordings of blue whale (*Balaenoptera musculus*) vocalizations in the Gulf of Corcovado, northern Patagonia, Chile. Mar Mamm Sci 26:451–459

Cabrera E, Carlson C, Galletti B (2005) Presence of blue whale in the northern coast of Chiloé Island, southern Chile. Latin Am J Aquat Mammals 4:73–74

Clarke R, Aguayo-Lobo A, Basulto del Campo S (1978) Whale observation and whale marking off the coast of Chile in 1964. Sci Rep Whales Res Inst 30:117–182

Conway CA (2005) Global population structure of blue whales, *Balaenoptera musculus* ssp., based on nuclear genetic variation. PhD dissertation, University of California, Davis, CA

Cummings WC, Thompson PO (1971) Underwater sounds from the blue whale, *Balaenoptera musculus*. J Acoust Soc Am 50:1193–1198

Findlay K, Pitman R, Tsurui T, Sakai K and others (1998) 1997/1998 IWC-Southern Ocean Whale and Ecosystem Research (IWC-SOWER) blue whale cruise, Chile. Paper SC/50/Rep2. International Whaling Commission, Cambridge

Försterra G, Häussermann V (2012) Report on blue whale sightings (*Balaenoptera musculus* Linnaeus, 1758) in a narrow fjord during autumn-winter in southern Chile. Spixana 35:237–245

Galletti Vernazzani B, Carlson CA, Cabrera E, Brownell RL Jr (2012) Chilean blue whales off Isla Grande de Chiloe, 2004-2012: distribution, site-fidelity and behaviour. J Cetacean Res Manag 12:353–360

Hucke-Gaete R (2004) Distribución, preferencia de hábitat y dinámica espacial de la ballena azul en Chile: 1997-2004. PhD thesis, Universidad Austral de Chile, Valdivia

Hucke-Gaete R, Osman LP, Moreno CA, Findlay KP, Ljungblad DK (2004) Discovery of a blue whale feeding and nursing ground in southern Chile. Proc R Soc Lond B Biol Sci 271(Suppl 4):S170–S173

LeDuc RG, Dizon MG, Pastene LA, Kato H, Nishiwaki S, LeDuc CA, Brownell RL Jr (2007) Patterns of genetic variation in Southern Hemisphere blue whales and the use of assignment test to detect mixing on the feeding grounds. J Cetacean Res Manag 9:73–80

McCauley RD, Jenner C, Bannister JL, Cato DH, Duncan A (2000) Blue whale calling in the Rottnest trench, Western Australia, and low frequency sea noise. Paper presented at the Australian Acoustical Society Conference, Joondalup

McDonald MA, Calambokidis J, Teranishi AM, Hildebrand JA (2001) The acoustic calls of blue whales off California with gender data. J Acoust Soc Am 109:1728–1735

McDonald MA, Mesnick SL, Hildebrand JA (2006) Biogeographic characterisation of blue whale song worldwide: using song to identify populations. J Cetacean Res Manag 8:55–56

Mellinger DK, Clark CW (2003) Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. J Acoust Soc Am 114:1108–1119

Oleson EM, Calambokidis J, Burgess WC, McDonald MA, LeDuc CA, Hildebrand JA (2007) Behavioral context of call production by eastern North Pacific blue whales. Mar Ecol Prog Ser 330:269–284

Ramírez P (1983) Capturas y observaciones de la ballena azul *Balaenoptera musculus*, L, en Paita-Perú 1961-1966 y 1975-1982 IMARPE. Rev Com Perm Pac Sur 13: 97–102

Samaran F, Adam O, Guinet C (2010) Discovery of a mid-latitude sympatric area for two Southern Hemisphere blue whale subspecies. Endang Species Res 12:157–165

Samaran F, Stafford KM, Branch TA, Gedamke J, Royer JR, Dziak RP, Guinet C (2013) Seasonal and geographic variation of the southern blue whale subspecies in the Indian Ocean. PLoS ONE 8:e71561

Širović A, Hildebrand JA, Wiggins SM, McDonald MA, Moore SE, Thiele D (2004) Seasonality of blue and fin whale calls west of the Antarctic Peninsula. Deep-Sea Res II 51:2327–2344

Širović A, Wiggins SM, Hildebrand JA (2007) Blue and fin whale call source levels and propagation range in the Southern Ocean. J Acoust Soc Am 122:1208–1215

Spalding MD, Fox HF, Allen GR, Davidson N and others (2007) Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. BioScience 57:573–583

Stafford KM (2003) Two types of blue whale calls recorded in the Gulf of Alaska. Mar Mamm Sci 19:682–693

Stafford KM, Fox CG, Clark DS (1998) Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. J Acoust Soc Am 104:3616–3625

Stafford KM, Nieukirk SL, Fox CG (1999a) An acoustic link between blue whales in the eastern tropical Pacific and the northeast Pacific. Mar Mamm Sci 15:1258–1268

Stafford KM, Nieukirk SL, Fox CG (1999b) Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. J Acoust Soc Am 106:3687–3698

Stafford KM, Nieukirk SL, Fox CG (2001) Geographical and seasonal variation of blue whale calls of the North Pacific. J Cetacean Res Manag 3:65–76

Stafford KM, Chapp E, Bohnenstiel DR, Tolstoy M (2011) Seasonal detection of three types of 'pygmy' blue whale calls in the Indian Ocean. Mar Mamm Sci 27:828–840

Thompson P, Findley L, Vidal O (1996) Underwater sounds of blue whales, *Balaenoptera musculus*, in the Gulf of California, Mexico. Mar Mamm Sci 12:288–293

Van Waerebeek K, Pastene LA, Alfaro-Shigueto J, Brito JL, Mora-Pinto D (1997) The status of the blue whale *Balaenoptera musculus* off the west coast of South America. Paper SC/49/SH9. International Whaling Commission, Cambridge

Williams R, Hedley SL, Branch TA, Bravington MV, Zerbini AN, Findlay KP (2011) Chilean blue whales as a case study to illustrate methods to estimate abundance and evaluate conservation status of rare species. Conserv Biol 25:526–535

Editorial responsibility: Ana Cañadas, Madrid, Spain

Submitted: October 30, 2012; Accepted: November 8, 2013
Proofs received from author(s): March 5, 2014