Model-based abundance estimates and an assessment of minimum population status of blue whales off Chile from the 1997/98 SOWER survey

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ABSTRACT

The 1997/98 SOWER survey in Chile searched the region from 18°30′S to 38°S. Although the primary intent of the surveys was to maximize blue whale encounters, survey coverage was sufficient to estimate abundance using model-based distance sampling ('count') methods. The abundance estimate for this survey region was 267 (95% CI: 214-332). This underestimates total population size, because inshore regions including Chiloé Island and the Gulf of Corcovado, where blue whales are now known to aggregate, were outside the survey area. However, it does address bias stemming from allocation of additional search effort in high-density areas to collect biopsy and photo-ID samples. A logistic model was fitted to the historical catches to find the lower bounds of the current status of this population: assuming that the abundance estimate applied to the entire population; using one value (6.04%) for intrinsic rate of increase; and using two catch scenarios (*i.e.*, whether historic catches came from Chile only (the 'Chilean' catch assumption), or from Chile, Ecuador and Peru (the 'southeast Pacific' catch assumption). If it is conservatively assumed that the baseline estimate applied to the entire population, then the population was at a minimum of 6-16% of pre-exploitation levels in 1997 under the Chilean catch assumption, and 5-12% of pre-exploitation levels under the southeast Pacific catch assumption.

INTRODUCTION

Two recognised subspecies of blue whales occur in the Southern Hemisphere: Antarctic (or true) blue whales (*Balaenoptera musculus intermedia*) and pygmy blue whales (*B. m. brevicauda*). During the austral summer, nearly all Antarctic blue whales are in the Southern Ocean south of 55°S, while pygmy blue whales are in more northerly waters, primarily in the Indian Ocean and around Australia and New Zealand (Ichihara, 1966; Kato *et al.*, 1995; Branch *et al.*, 2007; Branch *et al.*, 2009). Blue whales also occur off Chile, Peru and Ecuador, but it is not yet clear whether these blue whales are Antarctic blue whales or pygmy blue whales (Van Waerebeek *et al.*, 1997), or are a separate as-yet undescribed subspecies (Branch *et al.*, 2007; 2009). Until the taxonomy of south-east Pacific blue whales is resolved, it would be sensible to manage them as a separate unit.

The current status of south-east Pacific blue whales is unknown. Catches in the region came primarily from Chile, but some were also taken from Peru and Ecuador (Clarke *et al.*, 1978; Ramírez, 1983; Van Waerebeek *et al.*, 1997). Hundreds were caught in many years from the 1910s to 1960s in Chilean waters (Clarke *et al.*, 1978; Van Waerebeek *et al.*, 1997), and their proportion among catches of all species remained similar over time (Aguayo, 1974). The catches therefore provide little evidence for substantial population declines before the Southern Hemisphere-wide ban on catching blue whales in 1966. Current sighting rates in the region are relatively high compared to the Antarctic, particularly around the newly discovered feeding and nursing ground in the Chiloe-Corcovado region (southern Chile) (Hucke-Gaete *et al.*, 2003; Hucke-Gaete *et al.*, 2005; Galletti Vernazzani *et al.*, 2006).

The International Whaling Commission (IWC) is conducting an in-depth assessment of Southern Hemisphere blue whales. To that end, a ship-based survey was conducted outside the territorial waters of Chile in 1997/98 under the auspices of the Southern Ocean Whale and Ecosystem Research (SOWER) programme (Findlay *et al.*, 1998). In contrast to a previous analysis (Branch *et al.*, 2007, SC-59-SH8), we estimate minimum abundance of blue whales from data collected during that survey using model-based estimators. We also collate the available catch data, and present a simple population model to estimate the minimum status of the population based on new and historic abundance estimates.

METHODS

Survey narrative

The primary aim of the survey was to develop methods of distinguishing between Antarctic and pygmy blue whales, by collecting visual data, biopsy samples, acoustic recordings and photographs for photo-identification. For this reason, the

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survey was designed to maximize encounters with blue whales in the study area. A secondary aim was to conduct a line transect survey and collect typical line transect data on sightings, complicating the analysis of the line transect data.

Two vessels were involved in the survey, the *Shonan Maru* (SM1) and the *Shonan Maru No. 2* (SM2). Two concentrations of blue whales had been identified off Chile, off Iquique (18°30′S to 23°S and east of 72°W) and between Valparaiso and Talcahauna (31°S to 40°S and east of 75°W); these disjunct regions were to be the primary focus of the survey, although senior scientists were given leeway to modify the survey design depending on the initial results. Both vessels departed from Iquique (20°12′S 70°09′W) on the morning of 13 December 1997. The SM2 headed to 18°30′S and began surveying southwards starting at 06h00 on 14 December; while the SM1 embarked on a long transit to 38°S and began surveying northwards at 06h00 on 18 December 1997. The northern region off Iquique was quickly covered by the SM1, while the SM2 encountered several blue whales during transit between 23°S and 31°S, between the two intended survey areas. It was therefore decided to extend the northern survey region southwards, and the southern region northwards, to provide complete coverage of the region from 18°30′S to 38°S. However, the central region between 26°30′S and 31°S was surveyed using non-randomly placed survey legs instead of the zigzag design elsewhere. At the end of the survey, both vessels conducted further daytime search effort during the transit from 30°S to 51°43′S southwards to Punta Arenas during 2–9 January 1998.

Stratum definitions

Based on the manner of searching, four strata were defined (Figure 1): a North stratum was defined from 18°30′S to 26°30′S (zigzag tracklines), a Central stratum from 26°30′S to 31°S (non-systematic tracklines), a South stratum from 31°S to 38°S (zigzag tracklines), and a Transit stratum from 38°S to 51°43′S (tracklines parallel to the coast). The inner boundaries of the North, Central and South strata were defined as the 12 n.mile territorial boundary of Chile, and their outer boundaries by joining the vertices of the tracklines. For the Transit stratum, however, the defined boundaries were 3 n.miles on the outer sides of their tracklines during the southern transit.

Search mode

Primary search mode was defined as "BB" effort code, and was recorded in acceptable weather conditions, such that a blue whale blow could be seen at 1.5 n.miles or greater. The conditions generally implied wind speeds under 25 knots, and sea state under 6 on the Beaufort Scale. Surveys were conducted in passing mode for all sightings (i.e. the ship did not leave the trackline to investigate a sighting) except that when blue whales or suspected blue whales were encountered, the vessel shifted to closing mode and left the trackline. When closing on a sighting, acoustic data, biopsy samples, and photographs were taken, and species identity and school size was confirmed. Secondary targets such as right, humpback, minke or Bryde's whales could be closed on at the discretion of the senior scientist, provided this did not compromise the aim of maximizing the encounters with blue whales.

Abundance estimation

Sightings of "pygmy blue" and "unknown blue" whales were included in the model. A 3nm truncation distance and exclusion of a "true blue" sighting eliminated only 2 sightings from the analysis. Effort and sightings data were modelled using the density surface modelling engine in Distance 6.0, Beta 5 (Thomas *et al.*, 2007), which called the 'count method' (Hedley *et al.*, 1999; Williams *et al.*, 2006). Transects were split into segments approximately 2 nm in length. Start and end locations of the segments were calculated using the Geofunc add-in (Jeff Laake, National Marine Mammal Laboratory) for Excel. Depth of the midpoint of the segment was estimated by overlaying the tracklines on a bathymetry grid in ArcView 3.2 (ESRI Inc., Redlands, CA). The area effectively searched entered the model as an offset term, which considered the length of the trackline and the effective strip width as determined from two candidate detection functions (hazard rate and half-normal).

The DSM model was of the form:

$$n \approx te(longitude, latitude) + offset$$

A gridded data set was created, containing a value in every grid cell for each explanatory variable in the model. Grid cells were approximately 10km on a side (*i.e.*, 100km^2) for prediction. Values for the explanatory variables (latitude and longitude) were calculated for the midpoint of each grid square. The prediction grid data were passed to the descriptive model selected for each species in Distance, which called the predict.gam function in mgcv. The output of the model was an estimate of the predicted number of whale schools in each grid cell, based on each cell's latitude, longitude and area. Animal abundance was calculated by multiplying the predicted density in each cell by expected school size (from the size-bias regression in the detection function modeling step; Buckland *et al.*, 2001) and by the area of each cell, and taking the sum of all values in the grid. The 95% confidence intervals were computed using parametric (moving block) bootstrap (Thomas *et al.*, 2007).

Preliminary population model

A preliminary analysis is used to find the lower bounds of the current status of this population, by assuming that the abundance estimate applied to the entire population. This assumption will result in a conservative assessment of the status of Chilean blue whales.

A logistic model was fitted to the historical catches under with one default assumption for the intrinsic rate of increase, namely r=6.04% (SE=2.93%) (courtesy A. Punt, IWC Volume 11, Annex D). Two catch series were examined (source: C. Allison, International Whaling Commission, 26 October 2006): the first catch series included only land station catches listed as "Chile" (hereafter referred to as the Chilean catch assumption), while the second catch series included catches listed as "Chile", "Peru" and "Chile/Peru/Ecuador" (hereafter referred to as the southeast Pacific catch assumption). Catches of unspecified species in Chilean waters (in years 1908–11, 1913, 1927, 1934–35; totalling 1,229 whales), were assumed to include 31.5% blue whales—the average over 1912–26 according to Van Waerebeek *et al*. (1997). The carrying capacity was estimated that would result in an abundance in 1997 equal to the baseline abundance estimate, assuming that the population increased according to a logistic model:

$$N_{1905} = K$$

$$N_{y+1} = N_y + rN_y\left(1 - \frac{N_y}{K}\right) - C_y$$

where:

N_y is the abundance in year y

r is the annual intrinsic rate of increase

K is the carrying capacity

C_y is the catch in year y

RESULTS

Distribution and abundance estimates

During the primary survey, most sightings of blue whales (15 of 23) were in the Central stratum, although blue whales were sighted in all strata (Figure 1, Table 1). Total primary search effort was 2,580 n.miles (3,585 n.miles including transits). The preferred detection function was a half-normal with a truncation distance of 3nm (Figure 2). Mean school size was 1.21 (se=0.50). The model-based abundance estimate (Figure 3) for the designed survey region (*i.e.*, excluding areas covered during transit legs) was 267 (95% CI: 214-332).

Preliminary population model

Total catches were 4,288 from Chile alone, and 5,782 from Chile, Peru and Ecuador, similar to a previous total estimate of 5,878 (Van Waerebeek *et al.*, 1997). Except for a gap during World War II, the catches were at consistent levels from the 1910s to the 1960s (Figure 4).

Population trajectories from the logistic model (Figure 5) show consistent initial declines from pre-exploitation abundance (K) of 2,000–6,200, stabilization or increases during World War II, and steeper declines in the 1950s and 1960s, before stabilization or recovery to the present. If it is conservatively assumed that our baseline, minimum abundance estimate applied to the entire population, then the population was at a minimum of 6-16% of pre-exploitation levels in 1997, under the Chilean catch assumption, and 5-12% of pre-exploitation levels under the southeast Pacific catch assumption (Figure 5). These sample trajectories represent minimum bounds since the 1997 abundance estimate refers to only a portion of the total population.

DISCUSSION

Survey coverage and design

The survey was not intended to produce abundance estimates as a primary aim, but rather to maximize the probability of encountering blue whales. Density surface modelling was used to take into account spatial bias in survey effort (especially in the Central stratum, which was directed toward blue whales) to minimise bias in resulting abundance estimates.

The survey also did not cover the territorial waters of Chile (from land to 12 n.miles), or the region south of 38°S (except for the transits). Subsequent findings of a major feeding and nursing ground in the Chiloé-Corcovado region (Hucke-Gaete *et al.*, 2003), south and inshore of the main survey region, indicate that a major portion of their population was probably missed by the survey. In the Chiloé-Corcovado region, two separate photo-identification studies (with few inter-year resightings) have respectively catalogued 45 individual whales to 2005 (Hucke-Gaete *et al.*, 2005), and 143 individual whales to 2007 (B. Galletti-Vernazzani, pers. comm. 27 April 2007). Given these findings, the total abundance of Chilean blue whales is probably substantially greater than our survey estimates.

Abundance estimates

Estimating abundance of rare species is a perennially difficult problem, even in pragmatic terms of collecting sufficient sightings to fit statistical models. One method to resolve this issue is to allocate additional effort to high-density areas for filling out the detection function, and applying this detection function to the designed survey (Williams and Thomas,

2009). This approach was not possible in the case of the 97/98 SOWER cruise, in which abundance estimation was not the research priority and the planned (design-unbiased) survey was not followed. The alternative, model-based abundance estimation approach was a suitable alternative. Our model-based abundance estimate of 267 (95% CI: 214-332) is considered most appropriate for the region surveyed. This estimate fits well with expectations from previous research. Branch et al. (2007; SC/59/SH8) estimated an abundance of 452 (95% CI: 160-1300) using conventional distance-sampling methods that did not address the additional trackline placement in the high-density area of the Central stratum.

Implied status of south-east Pacific blue whales

Simple logistic models were fitted to the catch series to assess the status of blue whales in the region. If it is conservatively assumed that the baseline estimate applied to the entire population, then the population was at a minimum of 6-16% of pre-exploitation levels in 1997, under the Chilean catch assumption, and 5-12% of pre-exploitation levels under the southeast Pacific catch assumption. However, the real status of the population is likely better than these results indicate, for several reasons. Foremost, the survey abundance estimate is smaller than the total abundance of Chilean blue whales because the Chiloé-Corcovado region was not included. Additional blue whales may be present in other inshore waters, or in deeper waters than those surveyed. As estimates of south-east Pacific blue whales, these are further negatively biased because blue whales are present off Peru and Ecuador at the same time of the year (Donovan, 1984; Ramirez, 1985), but no account is taken of this in the model. Finally, it is not clear which catch series to use for the population modelling since the catches cannot easily be divided between Chile and Peru/Ecuador. Including Peru/Ecuador catches therefore results in further negative bias of the current status of Chilean blue whales. Further work is needed to obtain a more representative population model, by taking account of the uncertainty in the abundance estimate, the intrinsic rate of increase, and the catch series.

Nevertheless, this simple modelling exercise has some value. Most importantly, despite conservative assumptions, the 1997-98 abundance was estimated to be greater than 5% of pre-exploitation levels, an order of magnitude less depleted than Antarctic blue whales (Branch *et al.*, 2004; Branch, 2007). This result is supported by continued catches of hundreds of blue whales annually from the 1910s to the 1960s. In contrast, catches of blue whales in the Antarctic, South Georgia and southern Africa declined precipitously over time, both in absolute numbers and as a proportion of all species (Bannister and Gambell, 1965; Best, 2003; Branch *et al.*, 2004).

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Table 1. Summary statistics: stratum areas (A, n.miles^2), number of transect legs in each stratum (k), number of sightings (n), survey search effort (L, n.miles), and sighting rate (n/L, schools per 1000 n.mile) plus the CV of the sighting rate.

Analysis	Stratum	A	k	n	L	n/L	CV
Planned strata	North	58,059	7	2	876.0	2.3	0.70
	Central	33,491	16	15	838.4	17.9	0.86
	South	74,808	5	6	865.8	6.9	0.42
Planned strata + Transit legs	North	58,059	8	2	927.4	2.2	0.67
	Central	33,491	17	16	889.7	18.0	0.80
	South	74,808	9	9	1210.4	7.4	0.37
	Transit	12,563	8	2	557.5	3.6	0.90

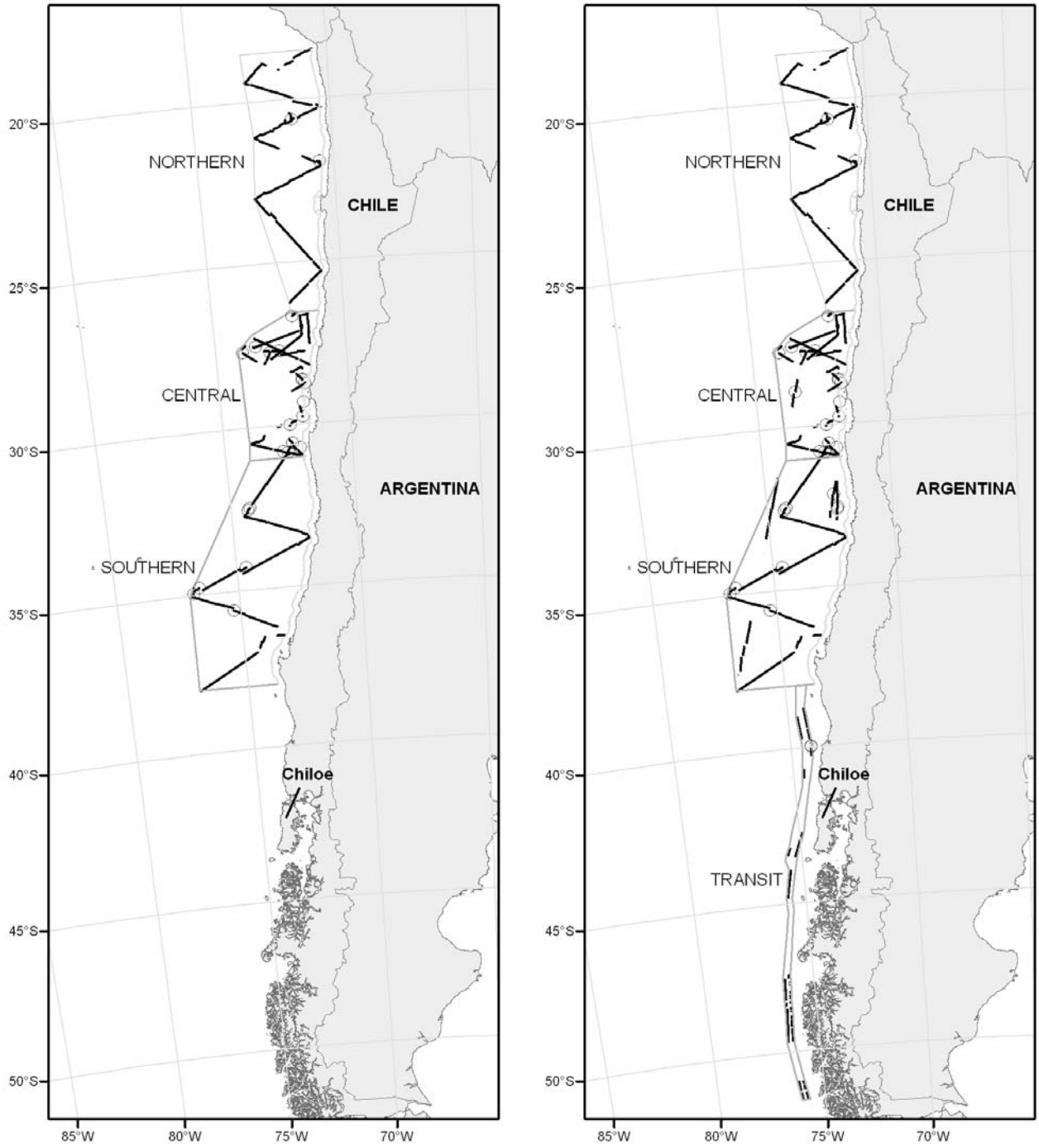


Figure 1. Sightings (circles), **s**urvey tracklines (black lines) and defined strata (grey lines) for the baseline analysis (left) and the alternative analysis (right). All transects (black lines in both left and right figures) were included in the dsm model fitting, but abundance was only predicted across the predefined strata (Northern, Central and Southern strata in the left-hand figure).

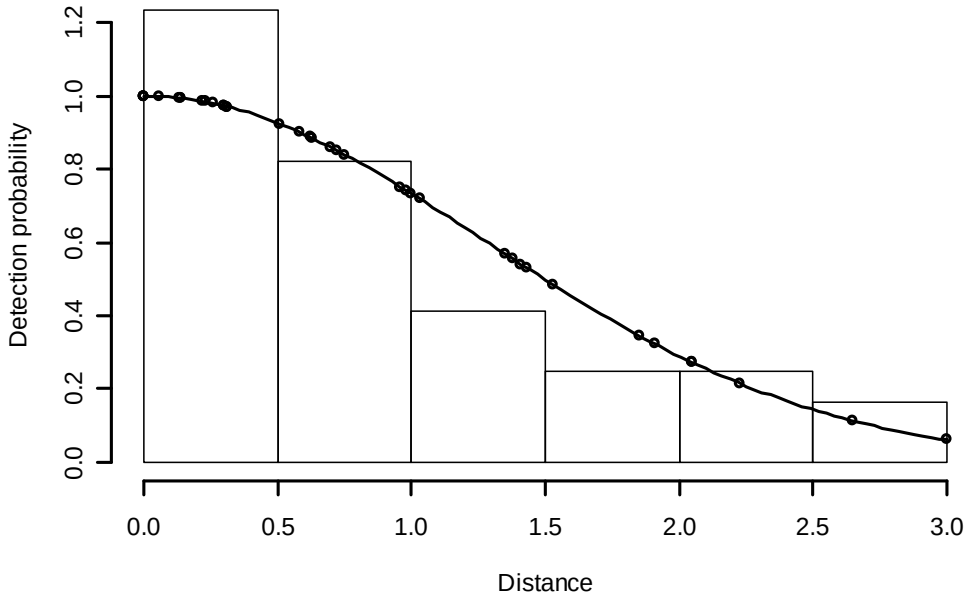


Figure 2. Detection function fits to the perpendicular distances of sightings from the trackline. Fits were to ungrouped data, but binned data are also shown here for illustrative purposes. The half-normal model was preferred. Lines correspond to the model fit, while dots show the perpendicular distance of each sighting.

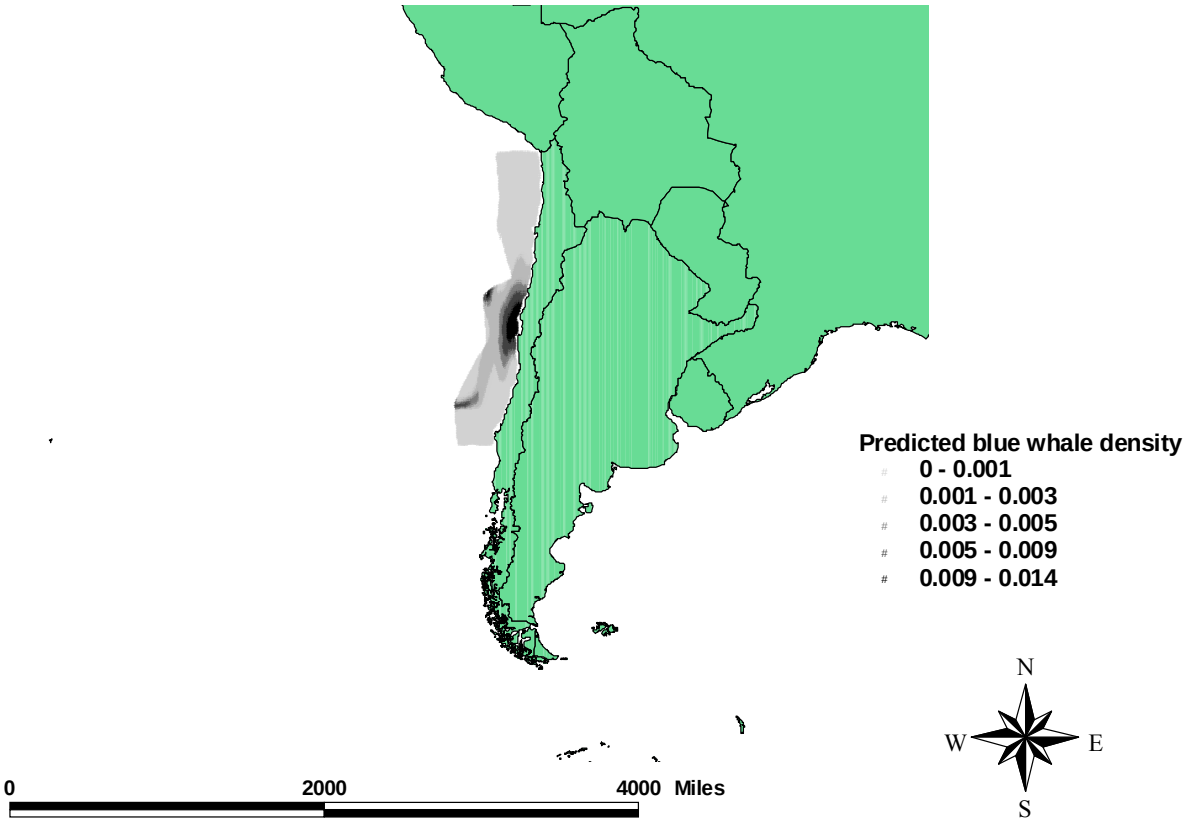


Figure 3. Density surface model of blue whale density in the survey region.

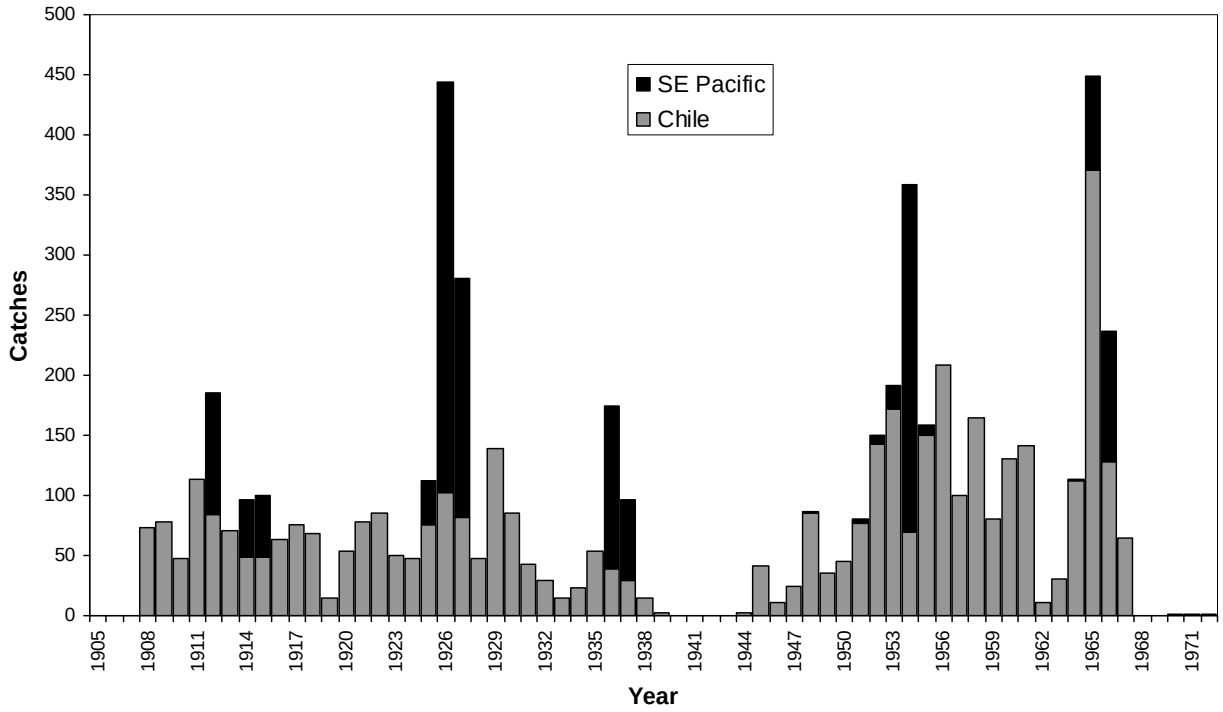
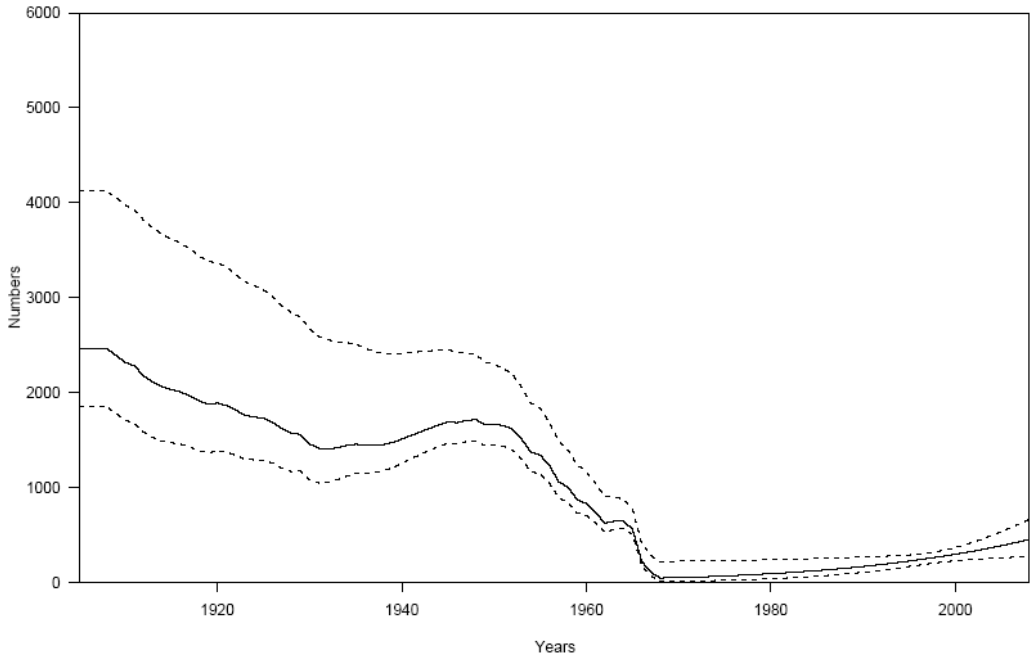


Figure 4. Historical catches from shore stations reported as coming from Chile (grey bars), and additional catches from the south-east Pacific (black bars, reported as either Peru or Chile/Ecuador/Peru).



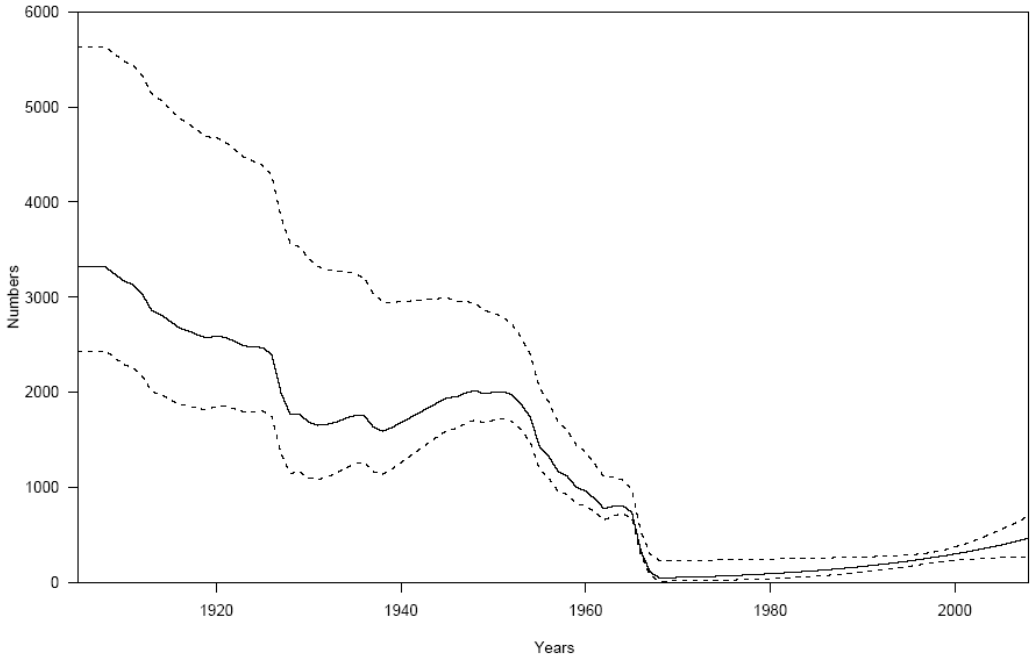


Figure 5 (top and bottom). Simple projections of abundance from logistic models fitted to the baseline survey estimate, under two catch history scenarios and an assumed value of intrinsic rate of increase, *r*, of 6.04% (SE=2.93%). The **top** figure assumes that catch series were catches reported from shore stations in Chile (the Chilean catch assumption). The **bottom** figure assumes that catches were reported from the entire south-east Pacific (Chile, Peru, Chile/Peru/Ecuador; *i.e.*, the southeast Pacific catch assumption). The trajectories represent the minimum status of Chilean blue whales, because the 1997-98 estimate applies to only a portion of the total population, but the bottom trajectory is the more pessimistic of the two.