# Abundance 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 intention of the surveys was to maximize blue whale encounters, survey coverage was sufficient to estimate abundance using line transect methods. The baseline abundance estimate, excluding transit legs, was 452 (CV = 0.56, 95% CI: 160–1300). This abundance estimate is negatively biased because inshore regions including Chiloé Island and the Gulf of Corcovado, where blue whales are now known to aggregate, were outside the survey area. If it is conservatively assumed that the baseline estimate applied to the entire population, then the population was at a minimum of 7–23% of pre-exploitation levels in 1997.

## 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.*, accepted; Branch *et al.*, in press). 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.*, accepted).

South-east Pacific blue whales differ to some extent from the other two subspecies in their genetics (Conway, 2005; LeDuc *et al.*, in press), acoustic call type (McDonald *et al.*, 2006), and female length at sexual maturity (Branch *et al.*, accepted), and are also geographically separated from the other two subspecies (Branch *et al.*, in press). However, in-depth morphological measurements and a possible type specimen are lacking. Aguayo (1974) examined 168 specimens caught at Quintay, Chile, in 1965/66 and 1966/67 and asserted that 10 were pygmy blue whales. Although no details were provided in the original publication, subspecies assignment was made on relative tail length (fluke notch to anus as a ratio of total length) and the ratio between breadth and length in the baleen plates (A. Aguayo, pers. comm., 10 April 2007). A 20.44 m physically immature female stranding on 2 January 1997 at Isla Don Martin, Peru, displayed more characteristics of an Antarctic blue whale than a pygmy blue whale, although the tail length: total length ratio was intermediate between the two subspecies (Van Waerebeek *et al.*, 1997). Other strandings in Chile and Peru have not been assigned to either subspecies (Van Waerebeek *et al.*, 1997; Hucke-Gaete *et al.*, 2005). This brief discussion highlights the taxonomic difficulties raised by south-east Pacific blue whales, without even touching on the added complication of the adjacent California-Mexico population of northern blue whales (*B. m. musculus*). Nevertheless, 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 currently conducting an in-depth assessment of Southern Hemisphere blue whales. As part of this assessment, 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. We estimate the abundance of blue whales in the survey region using the line transect data collected on this survey, collate the available catch data, and present a simple population model to estimate the minimum status of the population.

## 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**

We analysed the survey data using the program Distance 5.0 (Thomas *et al.*, 2005). Abundance estimates were obtained from the standard distance sampling formula:

$$N = \frac{A \cdot \bar{s} \cdot n}{2 \cdot w_s \cdot L}$$

where:
$N$ = abundance estimate
$A$ = area of stratum (n.miles$^2$)
$L$ = primary search effort (n.miles)
$w_s$ = effective search half-width for schools (n.miles)
$\bar{s}$ = mean school size
$n$ = number of schools sighted during primary search effort

Variance estimates and 95% lognormal confidence intervals were computed following Buckland *et al*. (2001). Search effort legs were defined to be straight line segments between vertices in the North and South strata, but entire days in the Central and Transit strata. Effective search half-width was estimated by fitting a detection function (either hazard rate or half-normal) to the ungrouped perpendicular distance data, after truncation at 3 n.miles. The simple mean school size was used, because the regression of log school size against the detection function $g(y)$ was not significant at the 0.15 level. Due to low sample sizes, sightings from all strata were pooled to estimate search half-width and mean school size.

**Baseline and alternative analyses**

The baseline analysis included only primary effort and associated sightings during the defined surveys, based on the North, Central and South strata. The alternative analysis additionally included the transit effort from Iquique to 38°S (SM1) and the end-survey transit from 30°S to 52°S by both vessels, and was based on the three strata in the baseline analysis plus the Transit stratum.

For both analyses, the half-normal and the hazard-rate models were fitted to estimate the detection function. Model selection uncertainty was incorporated in the analysis by averaging the estimated effective strip half-width for these two models using AIC-weighting (Burnham and Anderson, 2002) as follows:

$$\Delta_1 = AIC_1 - \min(AIC_1, AIC_2), \quad \Delta_2 = AIC_2 - \min(AIC_1, AIC_2)$$

$$w_1 = \frac{e^{-\Delta_1/2}}{e^{-\Delta_1/2} + e^{-\Delta_2/2}}, \quad w_2 = 1 - w_1$$

$$N_{ave} = w_1 N_1 + w_2 N_2$$

$$CV_{ave} = \frac{w_1\sqrt{(CV_1 N_1)^2 + (N_1 - N_{ave})^2} + w_2\sqrt{(CV_2 N_2)^2 + (N_2 - N_{ave})^2}}{N_{ave}}$$

where:

$N_1, N_2$ are the abundance estimates from the two detection functions

$CV_1, CV_2$ are the associated CVs for respective abundance estimates

$AIC_1, AIC_2$ are the Akaike Information Criteria (Akaike, 1973) for the two detection functions.

**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 three scenarios (0, 0.05, 0.1) for the intrinsic rate of increase. Two catch series are examined (source: C. Allison, International Whaling Commission, 26 October 2006): the first catch series included only land station catches listed as “Chile”, while the second catch series included catches listed as “Chile”, “Peru” and “Chile/Peru/Ecuador”. 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 estimated search half width was 1.61–2.00 n.miles except for the hazard-rate model fit to the alternative analysis (0.96 n.miles) (Table 2). Mean school size was 1.28–1.35. Based on AIC values, the half-normal model provided a better fit to the sightings data for the baseline analysis, but the hazard-rate model provided a better fit to the data for the alternative analysis (Table 3). Additional sightings included in the alternative analysis were all close to the trackline, explaining the much smaller estimated search half width from the hazard-rate model (Figure 2).

AIC-model-averaged abundance estimates for the survey region were 452 (CV = 0.56) for the baseline analysis and 753 (CV = 0.66) for the alternative analysis (Table 3). The higher estimate for the alternative analysis was not due to an increased sighting rate, nor to the addition of the Transit stratum (only 17 or 30 whales were estimated to be in this stratum), but because of a much narrower estimated search half-width from the hazard-rate model fit: 0.96 n.miles vs. 1.61 n.miles for the baseline analysis (Tables 1–2).

**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 3).

Population trajectories from the logistic model (Figure 4) 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. Depending on the assumed scenarios, the minimum abundance was 1–10% of *K*, the 1997 abundance was 7–23% of *K*, and current abundance is 7–44% of *K* (Table 4). 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 to maximize the probability of encountering blue whales. In reality, survey effort in the North and South strata followed tracklines that were independent from expected abundance, but survey effort in the Central stratum was more directed and may have biased the resulting 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

The baseline survey estimate of 452 (CV = 0.56) is considered to be the most appropriate for the region surveyed. The alternative analysis is included for completeness, but the additional transit tracklines were parallel to the coastline (and the expected gradient of blue whale density). Additionally, the sightings during the transits were typically close to the trackline, suggesting that searching effort may not have been as extensive as effort during the main survey. The higher alternative estimate of abundance of 753 (CV = 0.66) is almost entirely due to the narrower estimated search half-width obtained from the hazard rate model fit to the data (0.96 n.miles). This search half-width is much narrower than the half-normal model (1.70 n.miles), either model fitted to the baseline analysis (1.61–2.00), or estimated search half-widths for blue whales from the same vessels in the Antarctic of 1.57–2.08 n.miles (Branch and Butterworth, 2001; Branch, 2007).

### 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. Although the results indicate that the 1997 abundance was 7–23% of pre-exploitation levels, 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, the simple modelling exercise has some value. Most importantly, despite conservative assumptions, the 1997 abundance was estimated to be greater than 7% 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**. Components of the abundance estimates for the baseline and alternative analysis: 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 |
|---|---|---|---|---|---|---|---|
| Baseline | 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 |
| Alternative | 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 |

**Table 2**. Estimated search half-width ( $w_s$ **,** n.miles), mean school size ( $\overline{s}$ ), and abundance ($N$), with associated CVs, for the baseline and alternative analyses, when either half-normal or hazard-rate detection functions were fitted to the distribution of sightings.

| Analysis | Stratum | $w_s$ | CV | $\overline{s}$ | CV | $N$ | CV |
|---|---|---|---|---|---|---|---|
| Baseline Half-normal | North | 2.00 | 0.18 | 1.35 | 0.145 | 45 | 0.74 |
| | Central | | | | | 202 | 0.89 |
| | South | | | | | 175 | 0.48 |
| Baseline Hazard-rate | North | 1.61 | 0.41 | 1.35 | 0.145 | 55 | 0.83 |
| | Central | | | | | 251 | 0.96 |
| | South | | | | | 217 | 0.60 |
| Alternative Half-normal | North | 1.70 | 0.13 | 1.28 | 0.122 | 47 | 0.70 |
| | Central | | | | | 226 | 0.82 |
| | South | | | | | 209 | 0.42 |
| | Transit | | | | | 17 | 0.92 |
| Alternative Hazard-rate | North | 0.96 | 0.48 | 1.28 | 0.122 | 83 | 0.83 |
| | Central | | | | | 400 | 0.94 |
| | South | | | | | 369 | 0.62 |
| | Transit | | | | | 30 | 1.03 |

**Table 3**. Estimated abundance for each detection function, associated AIC values, and the AIC-weighted overall abundance estimates for the two analysis options.

| Analysis option | Detection function | N | CV | 95% CI | AIC | N (weighted) | CV | 95% CI |
|---|---|---|---|---|---|---|---|---|
| Baseline | Half-normal | 422 | 0.51 | (160; 1100) | 48.98 | 452 | 0.56 | (160; 1300) |
| | Hazard-rate | 523 | 0.63 | (160; 1700) | 50.69 | | | |
| Alternative | Half-normal | 500 | 0.44 | (210; 1200) | 56.53 | 753 | 0.66 | (230; 2400) |
| | Hazard-rate | 882 | 0.63 | (280; 2800) | 55.19 | | | |

**Table 4**. Simple projections of the minimum status of Chilean blue whales from a logistic model (pre-exploitation abundance = $K$), under different catch scenarios (Chile catches only, or all south-east Pacific catches) and different assumptions for $r$ (0, 0.05, 0.1). It was assumed that the abundance in 1997 ($N_{1997}$) was 452.

| Catch series | Chile only | Chile only | Chile only | SE Pacific | SE Pacific | SE Pacific |
|---|---|---|---|---|---|---|
| $r$ | 0 | 0.05 | 0.1 | 0 | 0.05 | 0.1 |
| $K$ | 4,740 | 2,783 | 2,002 | 6,234 | 3,721 | 2,644 |
| $N_{min}/K$ | 0.10 | 0.05 | 0.02 | 0.07 | 0.03 | 0.01 |
| $N_{1997}/K$ | 0.10 | 0.16 | 0.23 | 0.07 | 0.12 | 0.17 |
| $N_{2007}/K$ | 0.10 | 0.24 | 0.44 | 0.07 | 0.18 | 0.35 |

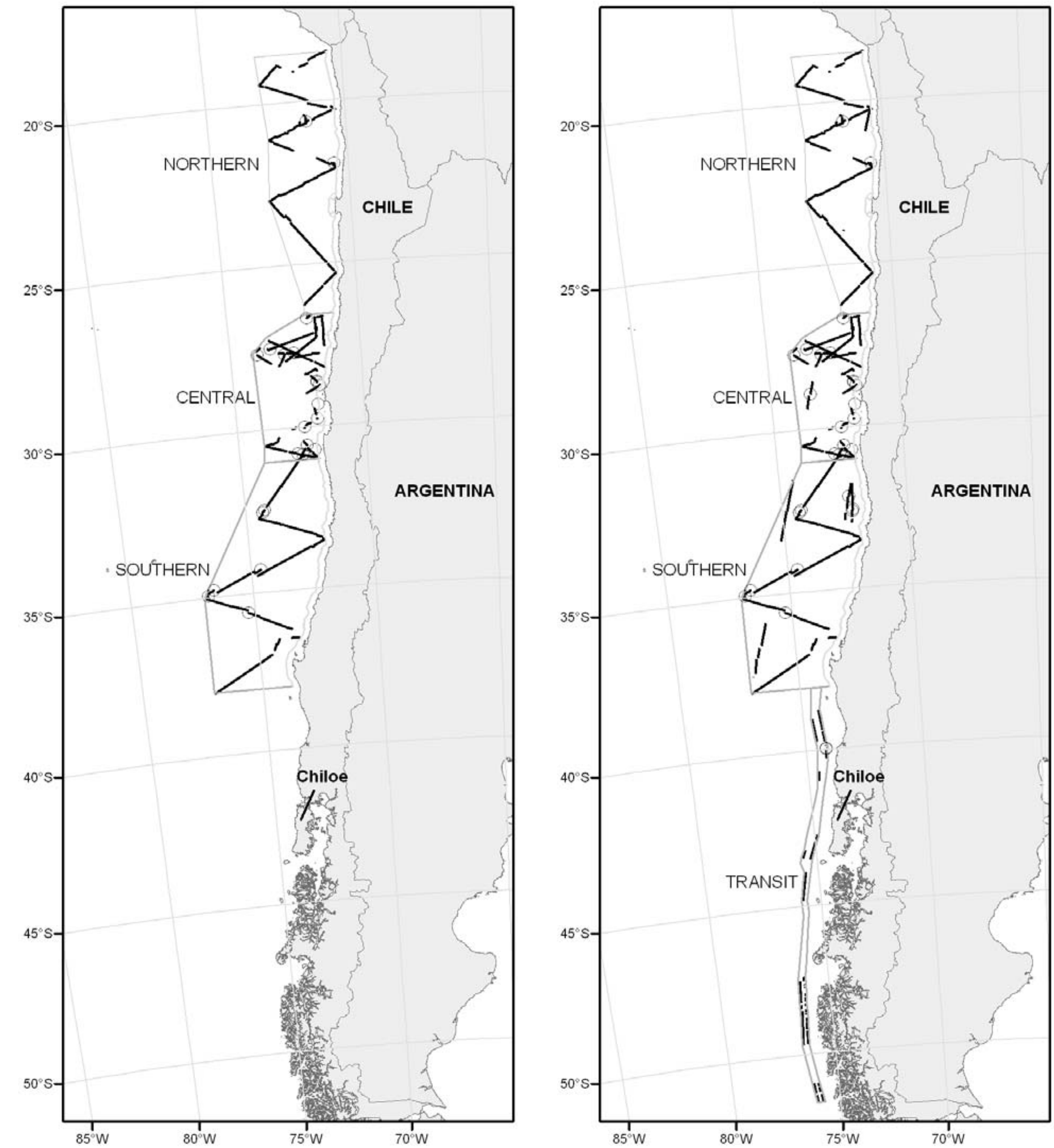


**Figure 1**. Sightings (circles), **s**urvey tracklines (black lines) and defined strata (grey lines) for the baseline analysis (left) and the alternative analysis (right). The baseline analysis excludes vessel transits to and from the defined survey region, while the alternative analysis includes tracklines and associated sightings during the vessel transits, and additionally includes a fourth stratum, the "Transit" stratum.

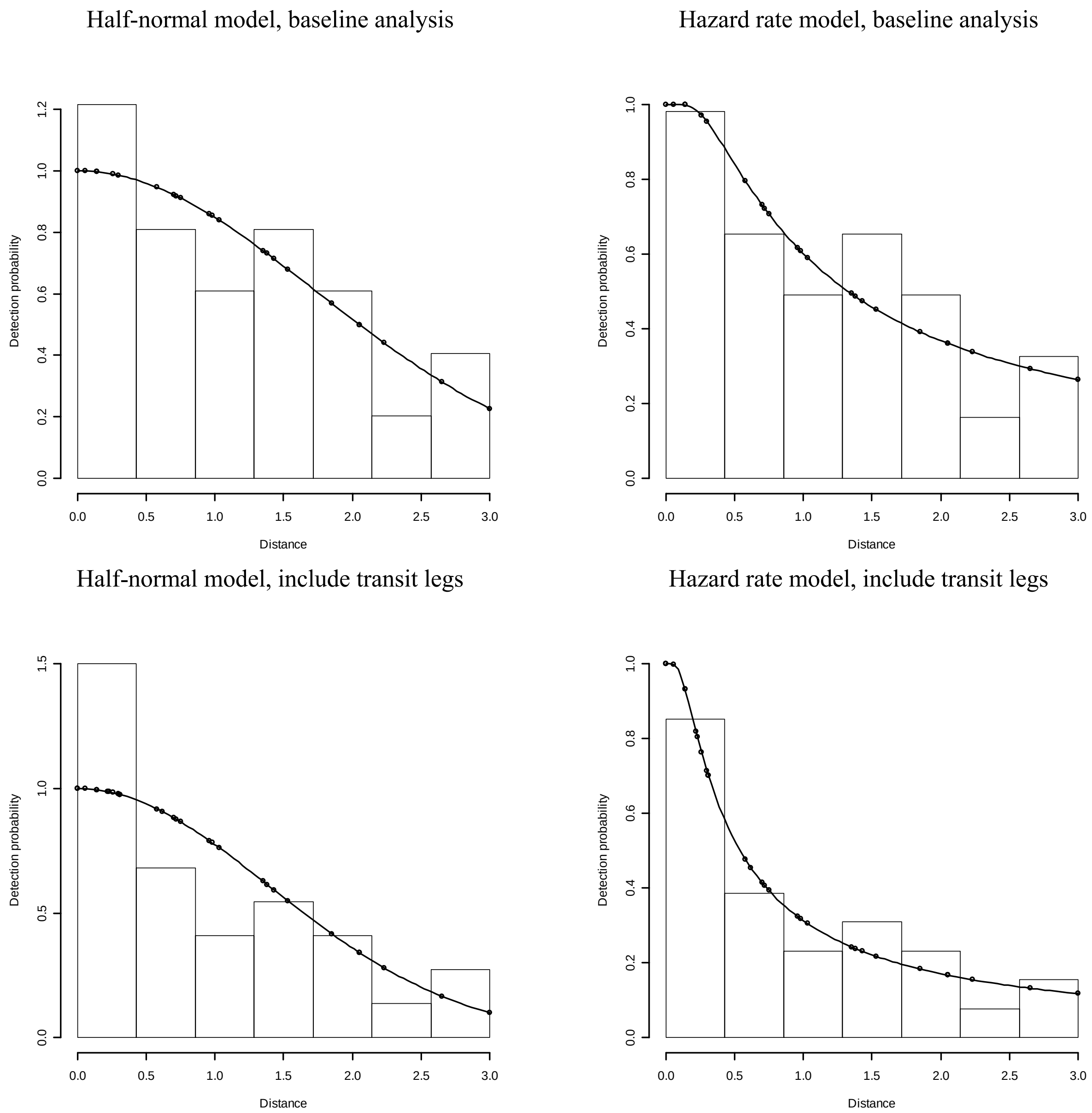


**Figure 2**. Detection function fits to the perpendicular distances of sightings from the trackline. Fits were to ungrouped data, but binned data are also shown here for illustrative purposes. Two models (hazard rate and half-normal) are fit to the data for the baseline and alternative analyses. Lines correspond to the model fits, while dots show the perpendicular distance of each sighting.

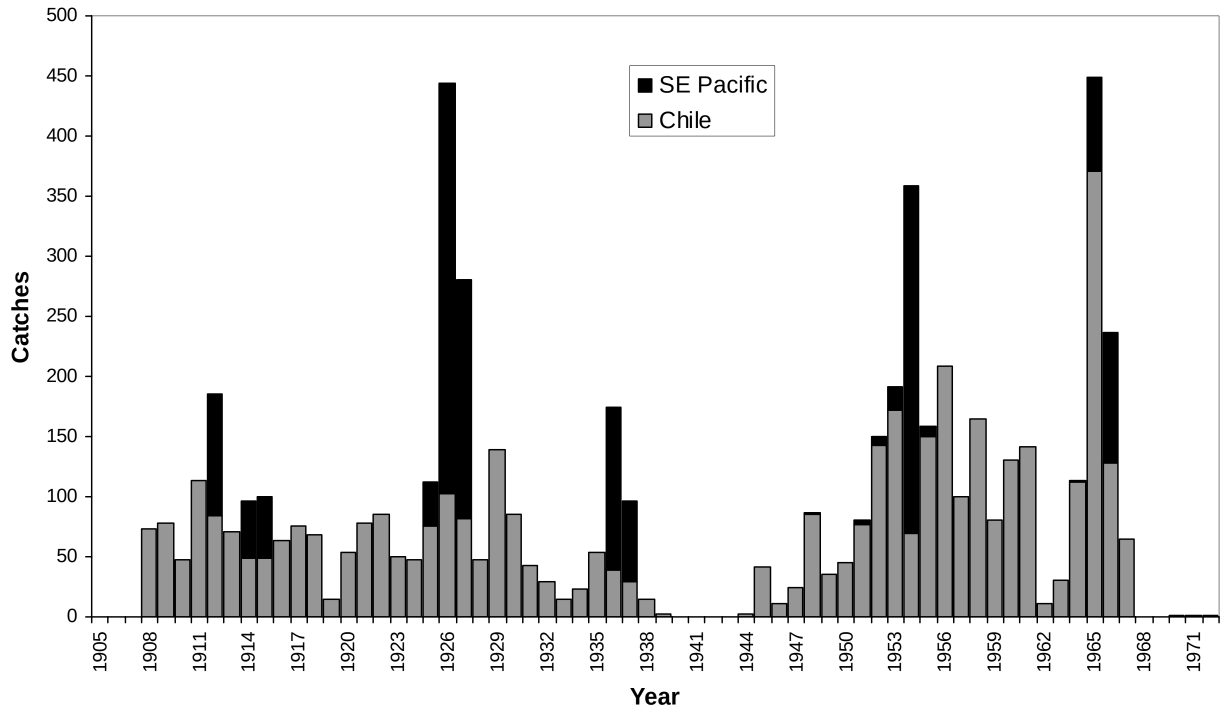


**Figure 3**. Historical catches from shore stations reported as coming from Chile (grey bars), and additional catches from the south-east Pacific (black bars, reported as either Peru or Chile/Ecuador/Peru).

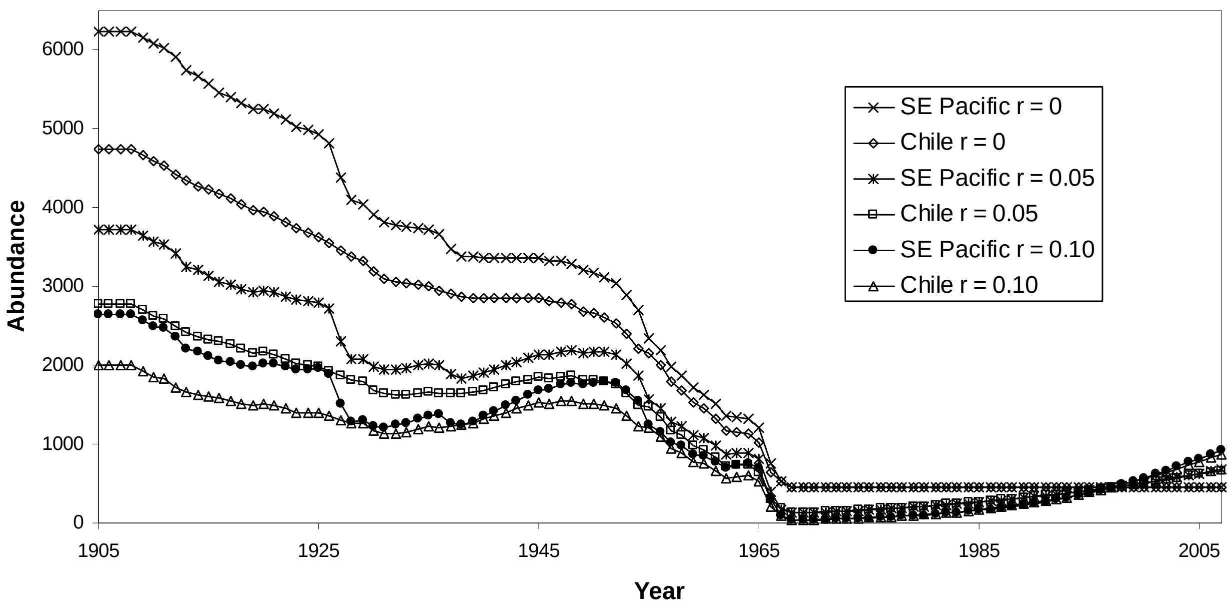


**Figure 4**. Simple projections of abundance from logistic models fitted to the baseline survey estimate, under two catch history scenarios and three assumed values of the intrinsic rate of increase ($r$ = 0.00, 0.05, 0.10). Catch series were assumed to be either catches reported from shore stations in Chile, or catches reported from the entire south-east Pacific (Chile, Peru, Chile/Peru/Ecuador). These trajectories represent the minimum status of Chilean blue whales since the 1997 abundance estimate applies to only a portion of the total population.