No evidence for recovery in the population of sperm whale bulls off Western Australia, 30 years since the cessation of whaling

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KEYWORDS

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ABSTRACT

Globally, sperm whale populations have been protected from large-scale commercial harvest for at least 25 years, yet there is no clear evidence of recovery in any heavily exploited stock. This may indicate that whaling has long-term demographic effects on this species, or that other endogenous or exogenous processes are inhibiting population growth. This study investigates the potential recovery of the depleted population of mature sperm bulls off Albany, Western Australia, a population reduced by 74% between 1955 and 1978. We conducted an aerial survey designed to replicate the method of the twin-engined ‘catcher’ planes employed by the Albany whaling fleet from 1968-1978, using the number of sperm bulls seen on each morning flight as a comparative index between bulls seen historically and in 2009. The mean number of sperm bulls seen on transect in 2009 was 2.43 ± 1.08, this increased to 3.38 ± 0.95 for all effort. Both 2009 estimates were substantially lower than the mean number seen in any of the years between 1968-1978, which ranged from 6.30 ± 1.18 (1976) to 12.45 ± 1.83 (1968). Conventional line transect analysis was also conducted in 2009, providing an estimated relative abundance of 29 (95% CI: 12-73) for all sperm whales and 14 (95% CI: 7-32) for sperm bulls. While combined visual and acoustic surveys conducted over multiple seasons are recommended to provide robust estimates of absolute population size in the future, this study nonetheless provides the first estimate of sperm whale abundance in Australian waters since the whaling era. The apparent decline in the number of sperm whales off Albany despite full protection is concerning, with implications for the management of sperm whales globally.

INTRODUCTION

Monitoring the long-term recovery of historically exploited great whale stocks ensures that any impediments to population growth can be recognised and managed (Baker & Clapham 2004). This is particularly important in light of the failure of some whale populations to show recovery, despite others of the same species increasing rapidly, often at their theoretical maximum rate, and a few to near pre-exploitation levels (e.g. western vs. eastern Pacific grey whales (Bradford *et al.* 2008); southwest vs. southeast Australian right whales (Carroll *et al.* 2011); East Australian (E1) vs. Oceanic (E2 & E3) humpback whales (Olavarria *et al.* 2007; Noad *et al.* 2011)). Although the causes of such differential population recovery are often poorly understood, factors such as a loss of genetic diversity (Reed & Frankham 2003) and the level of exposure to ongoing threats (Lotze *et al.* 2011) influence the capacity of a population to recover. It is therefore of concern to conservation scientists and management agencies to address data deficiency in regards to depleted whale populations, and adopt a case-by-case approach to population recovery efforts (Clapham *et al.* 1999).

In the 25-35 years since sperm whaling operations became uneconomical or were closed down following the 1986 moratorium, exploited sperm whale stocks can be expected to have shown signs of recovery at a theoretical growth rate of 1-1.1% (Whitehead, 2003; Chiquet *et al.* 2013). It is often assumed that sperm whale numbers have increased, and some populations that were not heavily whaled appear to be healthy (Gordon *et al.* 1998) or at least growing slowly (Gero *et al.* 2007). There has however, been little clear evidence for recovery in any heavily exploited population, notably the southeast Pacific (Whitehead *et al.* 1997) and Mediterranean (Reeves & Notobartolo di Sciara, 2006) stocks. This indicates that whaling may have effects on sperm whale demography that are felt for decades (Whitehead *et al.* 1997), or that other endogenous or exogenous processes have hampered population growth.

Sperm whales were hunted off Albany, Western Australia, where the continental shelf is narrow and drops sharply to 5000m (Fig 1). Modern whaling took place here from 1955 until 1978, with annual catches exceeding 400 individuals from 1961 (Bannister, 1968). This take contributed to the 3000-5000 individuals caught per year in the southern Australian region up to the mid-1970s (Bannister, 1974), an area thought to contain a single stock of sperm whales in terms of the demographic effect of exploitation (Bannister, 1969; Brown, 1981). This take resulted in substantial declines in the number of animals in the Albany region, particularly mature sperm bulls (35 feet and over), which constituted the primary target class. In 1979, females were estimated at 91% and males at just 26% of their pre-exploitation abundance (Kirkwood *et al.* 1980).

The availability of long-term historical data from the Albany sperm whaling operations provides an invaluable opportunity to assess the recovery of this population. The aim of this study is to provide an index of sperm whale abundance in the waters off Albany, Western Australia, that is directly comparable to estimates derived from the number of "catchable" bulls seen by spotter planes in the period 1968-1978. This should allow us to assess the recovery of the Albany sperm whale population in the period since whaling operations ceased. Further, we intend to provide a baseline index of relative abundance for this group, in order to inform ongoing management of sperm whales in Australian waters.

METHODS

Historical data selected for comparison with 2009

Sperm whales were caught at Albany from April through to the end of November 1955-1978 (Kirkwood, 1980). Aerial spotters were employed to assist the catch from 1962, first using a single-engined float plane (1962 – 1966), and then with a faster and more efficient twin-engined aircraft from 1967. The daily logs from these flights recorded the number of sperm whales sighted – in particular the number of "catchable" whales, i.e. sperm bulls over 35 feet.

We used data on sperm bull sightings from 1968-1978 as an index from the whaling era. Although it is almost impossible to match indices such as catch per unit effort (CPUE) between historic and contemporary studies, the use of the twin-engined aircraft during this period made the 'surveys' undertaken by the spotter planes replicable. We selected data from September – November for comparison, following the recommendation of Kirkwood (1980) that the greatest numbers of bulls were seen in this period. We then digitally encoded the historical data and checked them for anomalies. The mean number of bulls seen on the first morning flight was used as a relative index for comparison with data collected in 2009. This was believed to be the most appropriate index on the following basis:

i.) Historically, the afternoon flights did not record the whales thought to have been recorded during the morning flight.

ii.) The number of hours flown skews the index: longer flights tended to occur when few, if any, whales were seen, and shorter flights resulted from flights that encountered whales, since the spotter aircraft would then spend time assisting the whaling ships to locate and catch the whales (Kirkwood, 1980).

Survey area and design 2009

We followed a dedicated survey programme specifically designed by Kirkwood (1980) to enable monitoring of the Albany population post-whaling. The area denoted by 'Approximate search boundary' (Fig. 1, (Kirkwood, 1980)) estimates the area searched by the twin-engined aircraft from 1967-1978, and was selected as the survey area for this study. Coordinates were determined manually by referencing nautical charts against the map presented in Figure 1, then this area was searched using a standard grid of parallel transects. Trackline design was undertaken in *Distance* v5.0 Release 2 (Thomas *et al.* 2010), with parallel transects oriented perpendicular to the major axis of the survey region. The final design resulted in 12 transects approximately 10.5 nautical miles (nmiles) apart (Fig. 2), covering 386 nmiles on transect, and 630 nmiles in total, including transits to and from the airport and connecting legs between transects.

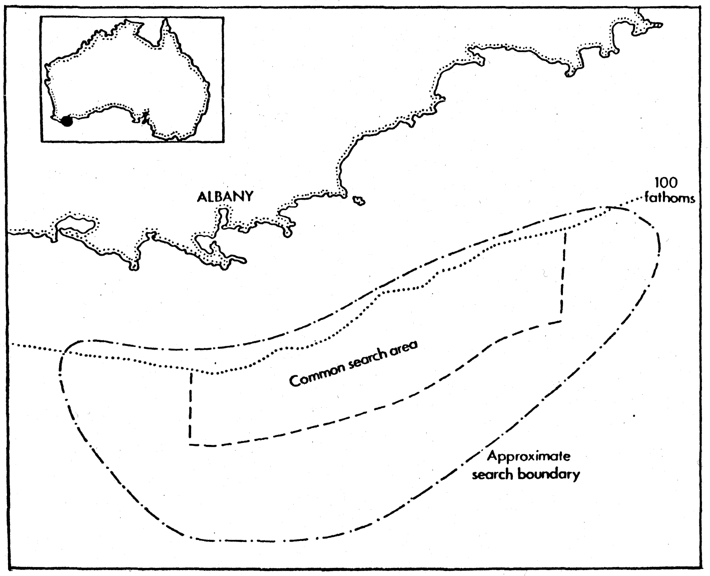

Figure 1: Search areas off Albany for commercial spotter aircraft. Area labelled 'Common search area' searched from 1962-1978; area indicated by 'Approximate search boundary' searched using twin-engined aircraft from 1967-78. Reproduced from Kirkwood and Bannister (1980)

During the course of the survey, the six easternmost and three westernmost transects were extended northwards. It was considered unlikely that the whaling operations would have regularly surveyed the extended transect area, however this modification was deemed necessary in order to cover more shelf area (Fig. 2) and increase the sample size. The sum of the extensions was 76 nmiles and this increased the total transect length to 462 nmiles and total flight length to 696 nmiles.

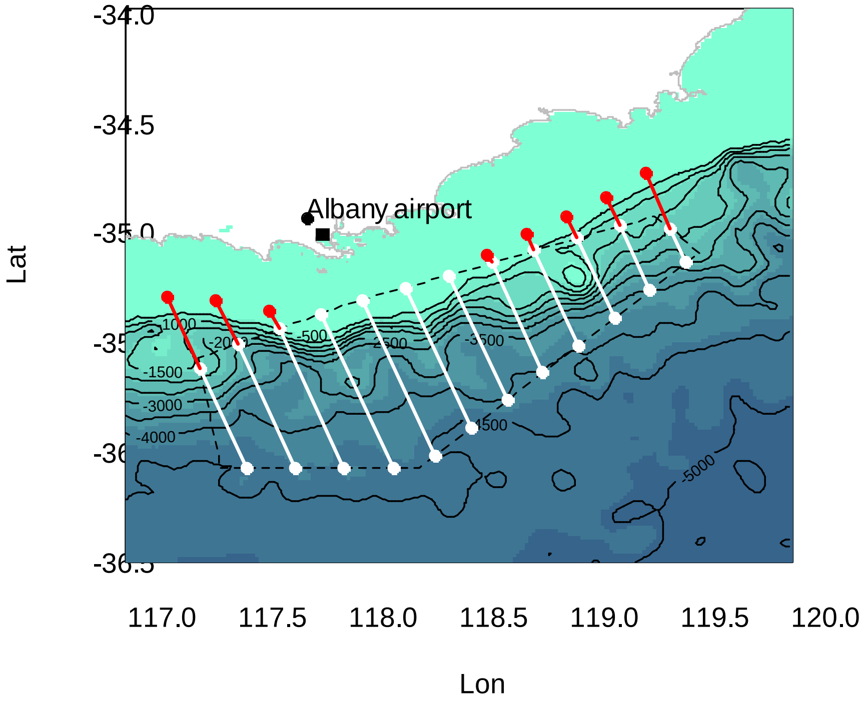

Figure 2: Waypoints, trackline design and survey region for the 2009 survey, with bathymetry detailed (in metres). Prior to 20th October, planned survey tracklines were as shown in white. From this date onwards, easternmost and westernmost transects were extended northwards (red waypoints and lines).

Data collection 2009

We aimed for an ideal of 60 surveys and scheduled our 2009 survey for September 10 to November 30 to maximise the chance of achieving this goal, following Kirkwood's recommendation that this was the period with fairest weather and highest numbers of sperm whales (Kirkwood, 1980). The aerial survey commenced September 25, 2009 (due to poor weather in the earlier part of September) and was completed on December 5, 2009. Data were collected using a single-platform configuration consisting of two experienced observers, one on each side of the aircraft. The aircraft, a twin-engined Cessna 337, flew at 1500ft (457m) at a speed of 120 knots (222 km/h). Sightings of animals were recorded and time-stamped on Microtrack digital voice recorders (M-Audio Microtrack 24/96) using Dick Clark aviation headsets and Aviall (Avix A4000) portable intercom systems. For each cetacean sighting, the declination angle of its abeam location was measured using a hand-held Suunto clinometer (Suunto PM-5/360 PC); species, group size and behaviour were also recorded. Times of sightings were taken as the times when the declination angle was recorded. Microtrack voice recorders were synchronized with the time from a GPS to match sightings with location. Sightings recorded on the Microtrack were transcribed into Excel spreadsheets after the flight. Digital SLRs were used to photograph sperm whales and other cetaceans to verify observer sightings and facilitate photogrammetric estimates of sperm whale length.

Line transect analysis 2009

Conventional line transect analysis involves fitting a detection function, (*g*) to some perpendicular distance data (*x*), integrating this function over the search width, and on the assumption that all objects are seen at zero distance, estimating the average detection probability within the survey strip (see, for example Buckland et al. 2001). The number of detections required for reliable estimation of a detection function is about 60, although it is often possible to fit reasonable models with fewer sightings, provided that the distribution of perpendicular distances is 'well-behaved' (notably, the distribution should exhibit a 'shoulder' at small perpendicular distances).

Data were analysed using conventional line transect estimation in the software *Distance 6.0* release 2 (Thomas *et al.* 2010). The objectives of these analyses were to obtain an estimate of (a) the average relative abundance of sperm whales in the area; and (b) the average relative abundance of adult bull sperm whales in the area. In *Distance*, two forms of the detection function were considered: the half-normal (with cosine adjustment terms) and the hazard-rate (also with cosine adjustments). Model selection was by Akaike's Information Criterion

(AIC). Each survey (where two flights undertaken on the same day constituted a single survey) was considered as a replicate, and the mean density was estimated as the effort-weighted average of the density estimates for each survey.

RESULTS

Historical data

A frequency distribution for the data from 1968-78 is shown as the barplots in Fig. 3, for sea states up to 2, and visibility at least fair. The distribution showed a high frequency of zero sightings (143), and a long tail, suggesting that when sperm whale bulls were seen it was usually in relatively small groups.

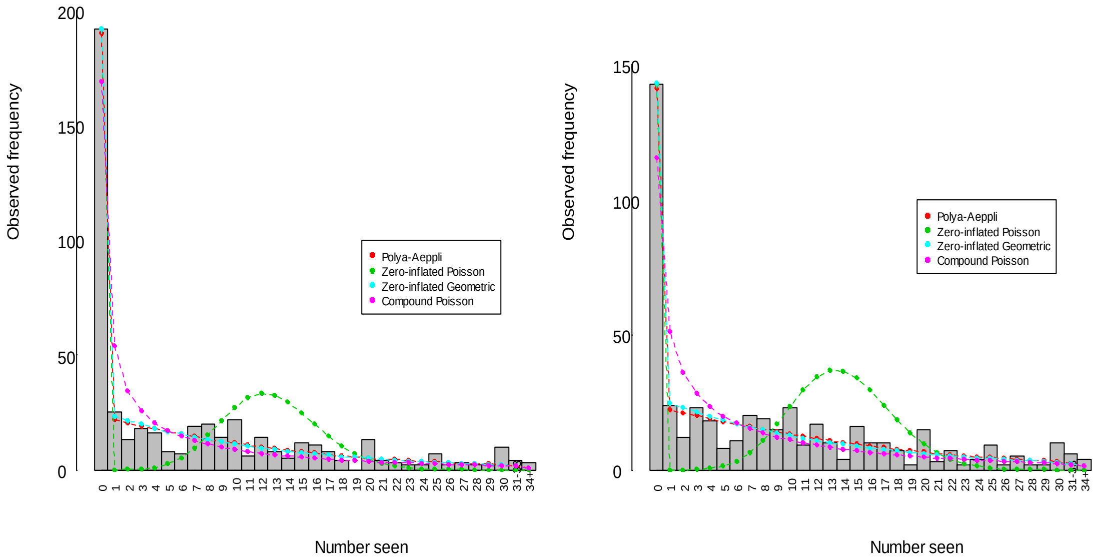

Figure 3: Distribution of number of bull sperm whales seen on the first morning flight in September-November from 1968-78. Conditions restricted to at least 'Fair' visibility and sea state up to Beaufort 2. Fitted distributions shown as described. Left panel = bulls seen in area. Right panel = total number of bulls

Four distributions for these data were considered: the Pólya-Aeppli distribution (with Poisson number of groups and Geometric group sizes); zero-inflated Poisson and Geometric distributions, and a compound Poisson distribution (with Gamma group sizes). Goodness-of-fit of these distributions were compared visually and using χ^2 goodness-of-fit tests. Test statistics are shown in Table 1. As can be seen in Fig. 3, the results in Table 1 suggest that either the Pólya-Aeppli distribution or the zero-inflated Geometric distribution fit the data reasonably; the former is marginally better according to its goodness-of-fit. We therefore focus our comparisons using this distribution.

	Pólya-Aeppli	Zero-inflated Poisson	Zero-inflated Geometric	Compound Poisson
Seen in area	101.5	143,240.2	109.3	194.8
Total seen	94.4	158,854.5	107.3	179.0

Table 1: χ^2 goodness-of-fit statistics from fitting Pólya-Aeppli, zero-inflated Poisson, zero-inflated Geometric and compound Poisson distributions.

The pdf of the Pólya-Aeppli distribution is given by

$$\Pr(N = x) = \begin{cases} e^{-\theta} & x = 0 \\ e^{-\theta} p^{x} \sum_{j=1}^{x} \binom{x-1}{j-1} \dfrac{[\theta(1-p)/p]^{j}}{j!} & x = 1, 2, \ldots \end{cases}$$

for $\theta > 0$ and $0 < p < 1$. The mean of the response is $\theta/(1-p)$ and variance $\theta(1+p)/(1-p)^2$. The log-likelihood function is given by

$$l(\theta, p) = \sum_{i=1}^{n} I(x_i = 0)(-\theta) + I(x_i > 0)\left\{-\theta + x\log(p) + \log\left[\sum_{j=1}^{x_i} \binom{x_i - 1}{j-1} \frac{(\theta(1-p)/p)^{j}}{j!}\right]\right\}.$$

The negative log-likelihood was minimized using the function ‘optim’ in R (R Development Core Team, 2009), and estimates of the mean number of bulls seen were calculated using the above formula. Percentile confidence intervals were calculated by simulation from the posterior distribution of the parameters (see, for example, Wood (2006 p.246-7)), and were compared with analytical confidence intervals calculated using the expression for the variance above. For the whaling data (with 488 morning flights), either method of interval calculation should suffice; for the survey data (with only 21 samples), the percentile method is preferable.

Line transect estimates of relative abundance 2009

Flights and data included in the analyses

A total of 61 flights was flown in 2009. Four flights were classified as training or video camera-testing flights. 18 flights were aborted with either no or very little survey effort (due to poor weather). 15 flights were completed full surveys; 12 flights were incomplete surveys and 12 flights were ‘half-surveys’ (two flights completed on the same day with all transects surveyed once). 40 sperm whale pods (160 individuals) were seen on-effort; an additional 8 pods (118 whales) were sighted off-effort. The survey area (outlined by the dashed lines in Fig. 2) spanned 13,125km^2. Search effort outside of this area (on the extended transects) was included in density estimation.

The area under the aircraft at an angle greater than 65° from the horizon (measured with an inclinometer) was not available for searching. At a flight altitude of 1500ft, this represents an area some 320m either side of the trackline. However, exploratory data analysis suggested that whilst some pods close to the trackline may have been missed, some sightings were made within the apparently ‘blind’ region. With so few sightings, it was decided to retain all sperm whale sightings in the analysis, but constrain the shape of the detection function to ensure that it had a ‘shoulder’ at small perpendicular distances.

Although with such low numbers of sightings the analysis options were restricted, incorporation of covariates in the scale parameter of the detection function was considered (Marques & Buckland, 2003). For this aspect of the analysis, only the half-normal detection function was considered. Covariates included cloud cover, sea state, wind speed and sightability code (a subjective measure of the viewing conditions with possible values: Nil, Poor, Fair or Good). However AIC values suggested no improvement to the fit of the detection function compared to the perpendicular distance-only form, for which a simple half-normal (with no adjustments) was selected in preference to the hazard-rate form.

Estimated abundance, $\hat{N}$, is given by:

$$\hat{N} = \frac{A \cdot \hat{E}(s) \cdot n}{2L\hat{\mu}},$$

where A is the survey area; $\hat{E}(s)$ is the estimated mean pod size; n is the number of detections within a perpendicular truncation distance (w) of the transect line; L is the length of trackline surveyed on effort; and $\hat{\mu}$ is the estimated effective strip half-width ($\int_0^w \hat{g}(x)dx$). Estimated mean pod size was estimated by regressing the log (observed pod size) against $\hat{g}(x)$, thus accommodating greater detectability of larger pods

The Pólya-Aeppli distribution was also fitted to the relatively sparse 2009 data. These data were derived from the 21 completed surveys. The data and fitted distributions are shown in Fig. 4 (using the same frequency bins as for the whaling data).

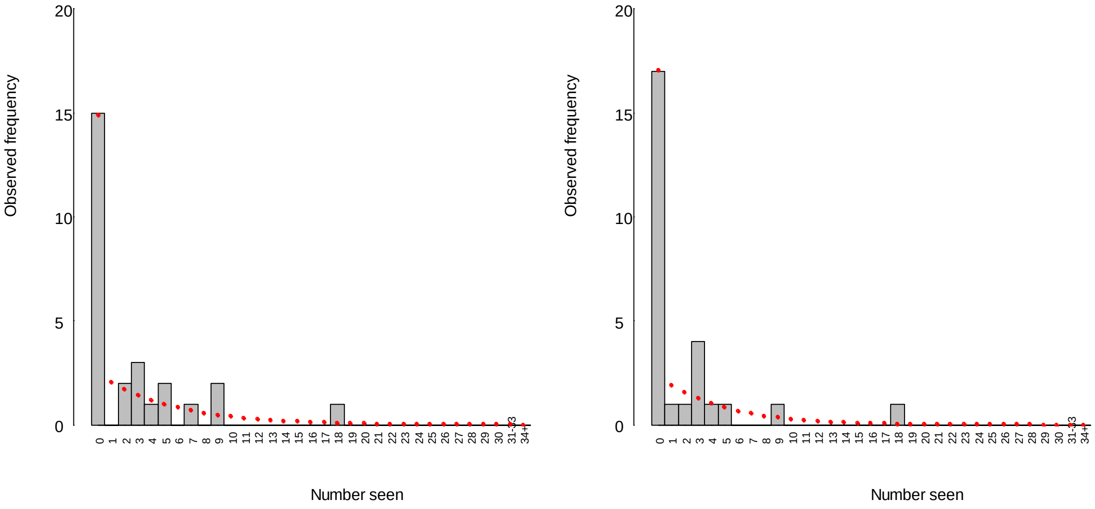

Figure 4: Distribution of number of bull sperm whales seen on each completed survey during the 2009 survey. Conditions restricted to at least ‘Fair’ visibility and sea state up to Beaufort 2. Red circles show fitted Pólya-Aeppli distribution. Left panel is for all sightings and effort for full and half-surveys. Right panel is the on-effort data only.

Comparing historical abundance with 2009

There is an apparent decreasing trend in relative abundance from 1968-78 (Fig. 5). In 1968 the mean number of bulls seen per first morning flight was 12.44 ± 1.83 this stayed above 10 until 1972, dropping as low as 6.30 ± 1.18 by 1976, though recovering slightly in the last two years of whaling. In 2009 using all sightings, including sightings made off-effort or beyond the designated search area, the mean number of bulls seen per flight was 3.38 ± 0.95; this reduced to 2.43 ± 1.08 when only on-effort sightings were included. Assuming that the survey method employed in 2009 was comparable with that of the whaling era, these results indicate a decline in the number of bull sperm whales observed off Albany since the cessation of whaling in the area.

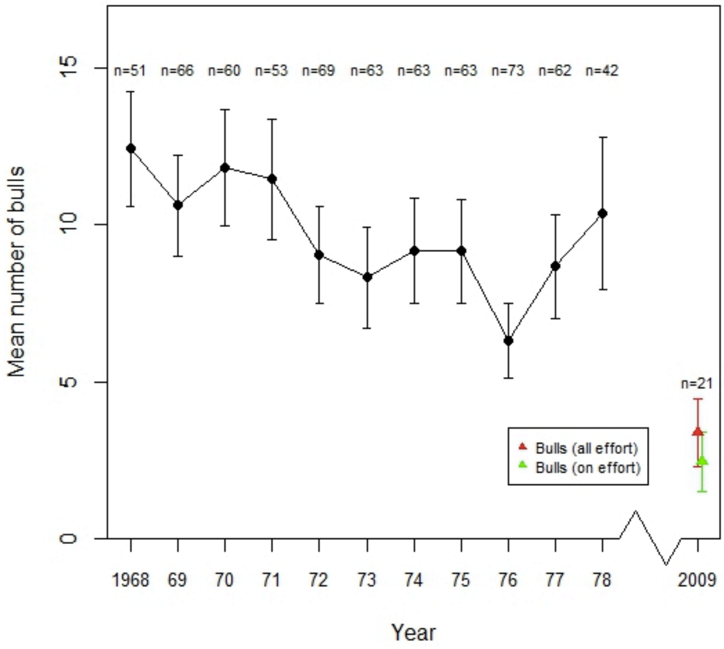

Figure 5: Comparison of the mean number of bulls seen on the first morning flights from the September-November whaling data, and the mean number seen on the 2009 survey. Total numbers (solid line) are comparable with those plotted in Figure 2 of Kirkwood (1980). The red circle is the mean number of bulls seen during flights undertaken on the 2009 survey; the green circle is the mean number seen ‘on effort’ during this survey.

Year	Mean Bulls sighted ‘Total”
1968	12.45 ± 1.83
1969	10.63 ± 1.62
1970	11.85 ± 1.85
1971	11.48 ± 1.92
1972	9.04 ± 1.55
1973	8.33 ± 1.62
1974	9.20 ± 1.68
1975	9.16 ± 1.67
1976	6.30 ± 1.18
1977	8.68 ± 1.66
1978	10.38 ± 2.41
2009	3.38 ± 0.95
2009	2.43 ± 1.08 (on transect)

Table 2: Estimates of the mean number (± S.E.) of adult bull sperm whales 1968-1978 and 2009 as calculated from the estimated distribution of the numbers per flight (a Pólya-Aeppli distribution).

Relative abundance

A total of 48 pods of sperm whales (including cows, calves and juveniles in addition to adult bulls) were sighted on flights used in the analysis; 40 of these were ‘on effort’ and could potentially be used in the line transect analyses. Of these 40 sightings, 7 were excluded from the analysis since it was not possible to obtain measurements of their angle of declination, and hence no perpendicular distances could be calculated.

Results are tabulated in Table 3, separately for all sperm whale pods and bulls, and by the data (i.e. flights) used in the analyses. The estimates in Table 3 are derived from two sets of data: flights that constituted a full survey of the area ('Full only') and these flights plus some partially completed flights for which a reasonable amount of survey effort had been achieved ('Full+part'). Provided the effort on the partially completed flights was not correlated with whale density (and we have no evidence to suggest it was – completion of transects was weather-dependent), it follows that the estimates that include data from these flights are potentially more robust. Effort-weighting the estimates by survey yielded mean estimates during the period. Resulting 'best' estimates from the 2009 survey are 29 (95% CI: 12-73) for all sperm whales, and 14 (95% CI: 7-32) for adult bulls.

	Flights	Area (km^2)	n	L (km)	$\hat{E}(s)$	$\hat{\mu}$ (km)	$\hat{N}$
Adult bull sperm	Full+part	13,125	27	18,310	1.66 (1.26-2.20)	1.09 (0.80-1.48)	14 (7-32)
	Full only	13,125	22	14,495	1.82 (1.33-2.49)	1.05 (0.75-1.46)	17 (7-44)
All sperm	Full+part	13,125	31	18,310	2.93 (1.82-4.71)	1.08 (0.80-1.45)	29 (12-73)
	Full only	13,125	26	14,495	3.44 (1.97-6.00)	1.04 (0.76-1.43)	39 (13-115)

Table 3: Abundance estimates ($\hat{N}$) of sperm whales. n is the number of sightings within a perpendicular distance of 2km; L is the length of transect surveyed; $\hat{E}(s)$ is the estimated mean pod size; $\hat{\mu}$ is the estimated effective strip half-width. 95% confidence intervals are given in parentheses.

DISCUSSION

The apparent decrease in the number of mature sperm bulls at Albany between 1978 and 2009 is a surprising result given the absence of commercial whaling, the sole factor attributed to the initial population decline (Taylor *et al.* 2008). An inherent assumption that is made in comparative abundance studies such as this is that the method of data collection is consistent enough between the two survey periods to render the results comparable. This can be particularly problematic when comparing modern and historical datasets (Brown *et al.* 2011). In this study, although we faithfully followed the recommendations for survey design set out in the whaling era report (Kirkwood, 1980), information regarding the method was in some cases sparse. For this reason, there will undoubtedly be some minor differences in 'catching efficiency', i.e. the probability of detecting whales between the two periods. As a conservative measure, we have therefore refrained from conducting statistical tests to quantitatively compare the results of our survey with data collected during the whaling era, as the requisite assumption of constant proportionality may not hold.

In our original design we followed the recommendation of Kirkwood (1980) that sampling over the latter part of the whaling season would provide the fairest weather for the survey, and that historically the greatest numbers of sperm bulls were seen from September to November. Inclement weather experienced during the 2009 study reduced the number of morning flights to less than that in any of the years between 1968 and 1978 (27 in 2009 c.f. 42 – 74 in whaling era). While this number of flights was less than the ideal of 60 that we had aimed for, examination of the sightings rate across the 70 day survey period within 2009 shows that the rate of sperm bull sightings on successful flights was consistent, and consistently very low, across the survey. Careful scrutiny of the sightings rate within September, October and November for each of the 10 years of historical data also does not reveal any significant trends or interactions, suggesting that the period surveyed in 2009 was comparable with the whaling era data, despite missing some survey time.

The most parsimonious interpretation of the 2009 estimates is that the decrease in the number of sperm bulls at Albany found by this study is real. Even the most conservative interpretation of the results would suggest that if there had been any significant increase (or at least no decline) in the number of sperm bulls at Albany between

1978 and 2009, our survey would have detected it. We explore some factors that may have led to a reduced numbers of sperm bulls being seen at Albany in 2009 below.

Recent demographic analysis has shown that sperm whale populations are potentially so fragile that they could experience decline with even a slight decrease in adult survivorship, and could face extinction with the occurrence of a major stochastic event (Chiquet *et al.* 2013). The life history traits of sperm whales such as slow rates of reproductive and social maturation, and low fecundity underpin this vulnerability (Best, 2005). It also appears that populations of sperm whales and other odontocetes may be intrinsically less resilient to exploitation than mysticetes with similar life history characteristics, due to behavioural and social traits (Wade *et al.* 2012), and that this has been compounded by sex-biased harvest (Whitehead *et al.* 1997).

Whitehead et al. (1997) argued that a catch biased towards mature sperm bulls may contribute to a depression of reproductive rates through a demographic Allee effect, due to the difficulty of females finding a suitable mate. In the Galapagos, mature males were observed attending aggregations of females on 75% of days during the breeding season, yet pregnancy rates remained low (Whitehead *et al.* 1993). This may indicate that females are highly selective in mate choice, and require a large pool of males from which to choose a mate. Alternatively, similar to African elephants (Slotow *et al.* 2000), there may be some mechanism of male sociality that is necessary for breeding success (such as a dominance hierarchy) that is dysfunctional with a substantially reduced number of males in the population (Whitehead *et al.* 2003).

Pregnancy rates of harvested females at Albany were observed to decline significantly between 1963-1964 and 1978, coincident with the reduction in bulls (Kirkwood *et al.* 1980). This suggests that a shortage of adult males due to biased harvest likely had a negative effect on population trajectory. In the Galapagos, the proportion of males in the population remained as low as 2-3% in the early 1990s (Whitehead, 1990; 1993), less than a quarter of their expected numbers (Whitehead, 1990). By contrast in 2009, the sex ratio off Albany was close to 1:2, suggesting some return towards preharvest sex ratios. Perhaps given the degree of sexual bimaturism in sperm whales (Best *et al.* 1984), this return has not been translated into population recovery as a whole.

Although the catch of female sperm whales at Albany was significantly less than that of males, depressed pregnancy rates were predicted to cause a decline in the number of mature females in the population until they reached 65% of their initial abundance in 1989 (Kirkwood *et al.* 1980). Female sperm whales aggregate into units of both related and unrelated individuals (e.g. Ortega-Ortiz *et al.* 2012) of different age classes, forming long-term multilevel associations (Whitehead, 2003; Whitehead *et al.* 2012). A loss of matriarchs from these units may have fragmented these associations and caused a loss of cultural knowledge (Whitehead, 2003). In elephant societies that are structured similarly to those of sperm whales, it is the oldest females that harbor much of the cultural knowledge such as predator evasion (McComb *et al.* 2011), and it is possible that older female sperm whales may possess knowledge such as the location of occasional feeding grounds. Removal of a significant number of these individuals from social groups may serve to reduce female fitness and affect the population more broadly, as the demography of sperm whales is most sensitive to mortality of adult females (Chiquet *et al.* 2013).

In addition to the potential long-term effects of whaling on demography, there remain a number of extraneous threats that could also contribute to a decline in sperm whale populations. High levels of organochlorines were found in the tissues of mass-stranded sperm whales in southern Australia in the late 1990s (Evans *et al.* 2004). The concentrations of these marine pollutants are expected to increase at higher latitudes due to their circulation from source points via long-range atmospheric or marine transportation (Wania, 2003). These contaminants may have deleterious effects on the normal enzymatic activity of long-lived predators such as marine mammals, leading to reproductive impairment (Roos *et al.* 2012) and reduced immune function (de Swart *et al.* 1996). To what extent these substances may affect sperm whales is not known, however any effect could be highly significant in a vulnerable population that has low rates of recruitment and high sensitivity to mortality (Chiquet *et al.* 2013).

The other major threats identified for sperm whales include entanglement in fishing nets and environmental noise (Taylor et al. 2008). While entanglement in drift nets represents a major source of mortality for other stocks of sperm whales (e.g. the Mediterranean (Reeves & Notobartolo di Sciara 2006)), this is unlikely to be a major factor in southwestern Australia, where the density of fishing activity is comparatively low. Similarly, shipping strikes are unlikely to be of major concern in this region (although a shipping route traverses the study area, the volume of traffic is relatively low). Environmental noise in the form of seismic explorations is known to be audible to sperm whales (Madsen *et al.* 2006) and there are conflicting reports on the extent to which this noise may trigger behavioural responses (Mate *et al.* 1994; Madsen *et al*. 2002) or interfere with the complex vocalisations that sperm whales employ for hunting and socialization (Bowles *et al.* 1994, Madsen *et al.* 2002).

Although there has been long-term seismic exploration in relation to a petroleum deposit between Albany and Esperance along Australia's southern coast, the infrequency of this activity and the distance from the study site (>1000km from Albany) probably preclude this from being a major source of concern as it may be for example in the Gulf of Mexico. Nevertheless, the cumulative effect of multiple threatening processes such as bioaccumulation, noise and entanglement is poorly understood, and these interactions may be highly significant within a fragile population, requiring further investigation and long term monitoring.

The apparent decline in sperm whale numbers at Albany may have occurred as a result of emigration from the area rather than increased mortality or reduced fecundity within the population. There was a mass emigration of Sperm whales from the Galapagos, with whales moving to fill productive areas depopulated by whaling near mainland South America (Whitehead *et al.* 1997). However, as Albany was the focus of whaling in this region, localised depletion is unlikely to have occurred elsewhere. As there are no other available abundance estimates for sperm whales in Australian waters, it is impossible to ascertain whether sperm whales that once attended Albany have moved elsewhere within the region. Sperm whales are however highly mobile (e.g. Steiner, 2012), and thus would be expected to shift their distribution in response to environmental change.

Albany represented a primary feeding ground for sperm whales, with 70% of whales feeding prior to capture, primarily on deep sea squid (Bannister, 1967). Changes in patterns of productivity and prey availability since 1978 may have caused the whales to alter their distribution, attending more productive areas during the survey period. Intra and inter-annual variability in many sperm whale abundance estimates was highlighted in a review of cetacean line transect surveys (Kaschner *et al.* 2012), and is problematic for studies conducted within a single season that attempt to make assumptions regarding wider population parameters. We recognise that although September – November was found to be reflective of annual trends during the period 1968-1978, surveys in multiple seasons and years will ensure that intra-and inter- annual variability in attendance is captured in future surveys.

The line transect estimate of relative abundance for all sperm whales produced from the 2009 survey provides a baseline index against which future surveys may be compared. The deep, asynchronous dive patterns of sperm whales make visual surveys such as the current study inappropriate for making meaningful assessments of absolute population size, as sperm whales stay submerged for between 30 and 60 minutes per dive (Whitehead *et al.* 1991). Boat-based visual surveys miss an estimated 38% of sperm whale groups (Barlow & Rankin, 2005), and this figure will be far higher for aerial surveys in which transects are searched at greater speeds. No estimate exists for g(0) for aerial surveys of sperm whales, and it is widely accepted that integrated acoustic and visual surveys are required to produce absolute abundance estimates. We recommend that in order to determine a course of action for the management of sperm whales in southern Australia, combined acoustic and visual surveys be employed in multiple years to provide an estimate of absolute population size.

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