A combined visual and acoustic estimate of 2008 abundance, and change in abundance since 1997, for the vaquita, *Phocoena sinus*

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Abstract

A line-transect survey for the critically endangered vaquita, *Phocoena sinus*, was carried out in Oct-Nov, 2008, in the northern Gulf of California, Mexico. Areas with deeper water were sampled visually from a large research vessel, while shallow water areas were covered by a sailboat towing an acoustic array. Based on simultaneous visual and acoustic data in a calibration area, the probability of detecting vaquitas acoustically on the trackline was estimate to be 0.42 (CV=82%). Acoustic detections were assumed to represent porpoises with an average group size of 1.9, the same as visual sightings. Total vaquita abundance in 2008 was estimated to be 250 animals (CV=44%, 95%CI 110-564). The 2008 estimate was 56% lower than the 1997 estimate, an average rate of decline of 7.4%/year. A Bayesian analysis found a 91% probability of decline in total population size during the 11-year period, and 100% probability of decline in the central part of the range where estimates were more precise. The Refuge Area for the Protection of the Vaquita contained an estimated 49% of the population. While animals move in and out of the Refuge Area, on average half of the population remains exposed to bycatch in artisanal gillnets.

Key words: trend in abundance, endangered species, line transect, acoustic trackline detection probability, conservation

Introduction

The vaquita (*Phocoena sinus*), or Gulf of California porpoise, was described as a species in 1958 (Norris and McFarland 1958). From the time of its initial description, its limited range (Brownell 1986, Gerrodette *et al.* 1995, Silber 1990) together with bycatch in fishing nets (D'Agrosa *et al.* 2000, Vidal 1995) prompted concerns for its conservation status. The first abundance estimate in 1997 based on the full range of the vaquita (Jaramillo-Legorreta *et al.* 1999) confirmed low total numbers of the species (567, 95% CI 177 - 1,073). This abundance estimate combined with the mortality estimate of 78 vaquitas (D'Agrosa *et al.* 2000) suggested a mortality rate of about 14% (78/567), which exceeded possible growth rates for porpoises. Based on the 1997 estimate and a subsequent increase in the number of artisanal fishing boats, Jaramillo-Legorreta *et al.* (2007) projected that the population might have declined to 150 vaquitas by 2007. However, Jaramillo-Legorreta *et al.* (2007) did not quantify the precision of this number, nor estimate the probability that the population had declined, given the large uncertainties about population size, amount of bycatch, and number of fishing vessels. The main point of the paper was that conservation action was urgently needed to prevent extinction.

In response to these studies indicating a likely decline, and recognizing the lack of conservation action preceding the extinction of the Chinese river dolphin or baiji (*Lipotes vexillifer*) (Turvey 2008), in 2008 the Mexican government formed a recovery team, promulgated a conservation action plan (SEMARNAT 2008), and committed US$25 million to conservation efforts. To maintain and justify such a large financial commitment, the government of Mexico wanted rapid feedback on the efficacy of conservation actions. A joint US-Mexican research project in 2008 had the primary goal of developing new monitoring methods using autonomous acoustic devices, towed acoustic arrays or both (Rojas-Bracho *et al.* 2010). A secondary goal was to collect line-transect data for a current estimate of vaquita abundance. This paper reports on the line-transect effort and compares the resulting 2008 estimate of abundance to the previous range-wide estimate in 1997.

Methods

Study area

Transects were carried out between October 16 and November 25, 2008 in the northern Gulf of California, Mexico, where vaquitas are known to occur (Brownell 1986, Gerrodette *et al.* 1995, Silber 1990) (Fig. 1). In waters deeper than about 10m, a large ship with sufficient height to detect vaquitas visually >1km from the ship has been successfully used on previous surveys (Barlow *et al.* 1997, Jaramillo-Legorreta *et al.* 1999). In waters too shallow for a large vessel, vaquitas were detected acoustically with a hydrophone towed behind a sailboat.

Visual line-transect data

Visual search effort was conducted from the *David Starr Jordan*, a 52m NOAA oceanographic research vessel. A series of north-south transect lines 0.05° of longitude (4.75km) apart were laid out prior to the cruise, based on a random starting longitude. Line-transect methods were the same as a similar cruise in 1997 (Jaramillo-Legorreta *et*

al. 1999), except that only a single team of observers was used during the 2008 cruise. Briefly, a team of 3 observers using pedestal-mounted 25X binoculars and a fourth observer using 7X hand-held binoculars searched for vaquitas as the ship traveled along the trackline at 6 knots (11km/hr). All observers were experienced with field identification of vaquitas or harbor porpoises. When a marine mammal was sighted, angle and distance to the sighting were measured (Kinzey and Gerrodette 2001, 2003), and the fourth observer entered the data into a computer. Group size, Beaufort sea state, visibility and other sighting conditions were recorded. The computer was connected to the ship's Global Positioning System to record the position of all data events. Occasionally the ship had to deviate from the planned trackline to avoid fishing nets or vessels, but otherwise the ship searched continuously in passing mode and did not approach sightings.

Acoustic line-transect data

A stereo hydrophone array was towed 50m behind a 24-foot (7.3m) Corsair trimaran, the *Vaquita Express*. The shallow draft of this sailboat allowed sampling in shallow water while minimizing disturbance. Following initial trials, transects were laid out to provide even spatial coverage and to sail at 4-5 knots (7-9km/hr) given prevailing wind conditions in the upper Gulf of California. When vessel speed dropped below 3.5 knots the sails were assisted by a 5HP four-stroke outboard engine.

Vaquitas produce distinctive narrowband (11-28kHz), short (79-193µsec), ultrasonic (120-150kHz) clicks with dominant frequencies ranging from 128-139kHz, that are arranged into click trains consisting of 3-57 clicks with highly variable interclick intervals (0.019-0.144 seconds, Silber 1991). These characteristics allow reliable detection of vaquitas and separation from other sources of biological noise. Clicks are similar to those described for other members of the Phocoenidae, including the harbor porpoise (*Phocena phocoena*), for which a reliable detector and classifier already exist (Gillespie and Chappell 2002).

The hydrophone array consisted of an oil-filled sensor section and two spherical elements separated by 25cm coupled to pre-amplifiers. The combined hydrophone and preamplifier sensitivity was approximately -161 dB re 1 V/µPa, and the response was approximately flat from 2 kHz to 200 kHz. Signals from each channel were routed through a buffer box to a National Instruments 6251 USB data acquisition board sampling at 480kHz and continuously recorded to a laptop computer using Logger 2000. The computer was connected to the ship's Global Positioning System and the ships track was recorded at 10 second intervals. Environmental covariates such as sea state and wind speed were recorded every half hour. Further details of the survey equipment and protocols can be found in Rankin *et al*. (2009).

Field recordings were reprocessed using the Click detector module of PAMGuard[1] using a standard trigger threshold set at 10dB, a digital high pass pre-filter at 40kHz (4 pole Butterworth) and a bandpass trigger filter set between 100 and 150kHz (4 pole Butterworth). PAMGuard was set to output detected clicks in a RainbowClick click file (*.clk) format[2]. Clicks were automatically classified using pre-configurable analysis

[1] http://www.pamguard.org/home.shtml

[2] http://www.ifaw.org/ifaw_united_kingdom/join_campaigns/protecting_whales_around_the_world/come_aboard_the_song_of_the_whale/download_cetacean_research_software/index.php

options within RainbowClick. We used a standard set of click parameters tuned to detect and classify harbor porpoise clicks. The classifier compared energy in a test (100-150 kHz) and control band (20-80 kHz) and classified a click as vaquita if the minimum energy difference between the two bands exceeded 3dB. Additionally, the classifier searched for narrow band clicks with a peak frequency between 120-150 kHz and classified the event as a vaquita if the estimated peak width was over 50% of the total energy and if the measured peak width was greater than 1kHz and less than 10kHz. Click length or duration was also used to help discriminate between vaquita clicks and other sources of biological noise, in this case the length of the waveform containing 50% of the total energy was measured and if the returned value was less than 2 milliseconds the click was classified as vaquita. A single experienced analyst (RS) reviewed the click files. Definite vaquita events were click trains containing 5 or more clicks matching Silber's (1991) description of vaquita clicks.

Perpendicular distances from the trackline were estimated by maximum likelihood, given a series of positions given by crossing the bearings of all clicks (D. Gillespie, pers. comm). Covariates for each 1km segment of effort included mean wind speed, mean sea state, mean vessel speed, mean underway (system) noise levels (dB) in the RainbowClick trigger band (100kHz– 150kHz), and the type of array.

Estimation of abundance and precision

The line-transect estimator of abundance was (Buckland *et al.* 2001)

$$\hat{N} = \frac{n\,\hat{s}\,\mathrm{A}}{2\mathrm{W}\,\mathrm{L}\,\hat{p}\,\hat{g}}, \qquad (1)$$

where A = area,

L = distance searched along trackline (effort),

W = strip width on each side of the trackline (truncation distance),

n = number of group detections,

$\hat{s}$ = estimated population mean group size,

$\hat{p}$ = estimated average of the detection function within distance W of the trackline,

$\hat{g}$ = estimated trackline detection probability [$g(0)$].

Random variables (n, s, p and g) are indicated with italics. We used the delta method (Taylor Series approximation) to calculate the precision of estimates. Fixed parameters (A, L and W) do not contribute to uncertainty. Using this method, the squared coefficient of variation (CV) of $\hat{N}$, assuming independence of the random variables, was

$$\mathrm{CV}^2(\hat{N}) = \mathrm{CV}^2(n) + \mathrm{CV}^2(\hat{s}) + \mathrm{CV}^2(\hat{p}) + \mathrm{CV}^2(\hat{g}).$$

We calculated a 95% confidence interval, assuming a lognormal distribution on $\hat{N}$, as

$$\left[\hat{N} / \exp\left(1.96\sqrt{\ln(1+\mathrm{CV}^2(\hat{N}))}\right),\ \hat{N} * \exp\left(1.96\sqrt{\ln(1+\mathrm{CV}^2(\hat{N}))}\right)\right]$$

(Buckland *et al.* 2001).

We used Distance 6 (Thomas *et al.* 2010) to estimate the average of the visual and acoustic detection functions, $\hat{p}_v$ and $\hat{p}_a$. We considered half-normal and hazard-rate detection functions, with and without cosine and polynomial adjustment functions (Buckland *et al.* 2001). Beaufort sea state was considered as a covariate that might affect detection probability, and noise level was also modeled as a covariate for the acoustic

data. Visual detections were truncated at W_v = 4 km and acoustic detections at W_a = 0.45 km. Model selection was based on Akaike's Information Criterion (AIC).

For the visual data, estimation was based on search effort and sightings that occurred during on-effort periods in conditions of Beaufort sea state ≤ 2. The probability of detecting vaquitas visually on the trackline from the flying bridge of the *David Starr Jordan* using a team of 3 observers with 25X binoculars was estimated to be $\hat{g}_v$ = 0.571 (CV = 32.7%), based on data from two independent observer teams (Jaramillo-Legorreta *et al.* 1999). For the acoustic data, estimation of abundance was based on effort and acoustic detections on transects, although estimation of the detection function included detections that occurred in transit to and from the transects. The probability of detecting vaquitas acoustically on the trackline (g_a) was estimated as described below. For both visual and acoustic data, variance of the number of detections was estimated empirically from 1km segments of effort using the default estimator in Distance.

Stratification

The study area was divided into 5 strata (Fig. 1). The deeper East stratum was surveyed visually by the *David Starr Jordan*, and the shallower North and West strata were surveyed acoustically by the *Vaquita Express* (Fig. 2). Both ships sampled the Calibration and Central strata. The Calibration stratum was an area within which the two vessels conducted simultaneous surveys for the purpose of estimating the acoustic trackline detection probability as described below. Outside of this period of simultaneous surveys, the *David Starr Jordan* carried out additional transects within the Calibration area; effort, sightings and estimates from this survey effort are designated "Calibration2" in Tables 1 and 2. The *Vaquita Express* also had additional transects within the Calibration stratum, but these did not cover the whole stratum and were not used for abundance estimation. However, the perpendicular distance of one detection from these transects was included in the estimation of the acoustic detection function.

We estimated abundance from visual data in the East, Central, and Calibration strata and from acoustic data in the West, Central, Calibration and North strata. We also estimated abundance within 2 areas proposed in the vaquita conservation action plan (SEMARNAT 2008) as protected areas within which gillnet fishing would be prohibited: Option 1 and Option 2 (Fig. 1). Option 1 is the existing Refuge Area for the Protection of the Vaquita. Abundance in the Refuge Area was estimated from visual sightings and effort within the Refuge Area, with all visual data used to estimate group size and detection function. Abundance in the Option 2 area was estimated as the sum of combined visual and acoustic estimates in the East, Central, Calibration and West strata, and a fraction of the estimated abundance in the North stratum prorated by area.

Acoustic trackline detection probability

We estimated g_a from simultaneous visual and acoustic surveys in the Calibration stratum from Oct 17-24, 2008. Using the estimator (1), and setting the visual and acoustic estimates equal,

$$\frac{n_{v,Cal}\,\hat{s}\,\mathrm{A}_{Cal}}{2\mathrm{W}_v\,\mathrm{L}_{v,Cal}\,\hat{p}_v\,\hat{g}_v} = \frac{n_{a,Cal}\,\hat{s}\,\mathrm{A}_{Cal}}{2\mathrm{W}_a\,\mathrm{L}_{a,Cal}\,\hat{p}_a\,\hat{g}_a},$$

where subscripts *v* and *a* refer to visual or acoustic data and *Cal* refers to the Calibration stratum. Solving for $\hat{g}_a$,

$$\hat{g}_a = \frac{n_{a,Cal} \mathrm{W}_v \mathrm{L}_{v,Cal} \hat{p}_v \hat{g}_v}{n_{v,Cal} \mathrm{W}_a \mathrm{L}_{a,Cal} \hat{p}_a}, \quad (2)$$

and, using the delta method,

$$\mathrm{CV}^2(\hat{g}_a) = \mathrm{CV}^2(n_{a,Cal}) + \mathrm{CV}^2(n_{v,Cal}) + \mathrm{CV}^2(\hat{g}_v) + \mathrm{CV}^2(\hat{p}_v) + \mathrm{CV}^2(\hat{p}_a).$$

Stratified estimates

We combined visual and acoustic data to produce a single estimate of density and abundance for each stratum. Mean group size of acoustic detections was assumed to be equal to mean group size of visual detections (see Results). We assumed average group size *s*, detection function averages p_v and p_a, and trackline detection probabilities g_v and g_a were the same for all strata.

Abundance in the East stratum N_E was estimated from visual data only.

$$\hat{N}_E = \left(\frac{\hat{s}}{2\mathrm{W}_v \hat{p}_v \hat{g}_v} \right) \left(\frac{n_{v,E}}{\mathrm{L}_{v,E}} \right) \mathrm{A}_E,$$

where the terms have been grouped to aid in interpretation. The first group contains terms assumed to be equal across strata. The second factor is the encounter rate (ratio of number of sightings *n* and kilometers of effort L), and is unique to the stratum. The product of the first two factors is density (number of animals per unit area), which is multiplied by the area of the stratum to obtain the estimate of abundance. The CV was calculated as

$$\mathrm{CV}^2(\hat{N}_E) = \mathrm{CV}^2(\hat{s}) + \mathrm{CV}^2(\hat{p}_v) + \mathrm{CV}^2(\hat{g}_v) + \mathrm{CV}^2(n_{v,E})$$

Abundance in the Calibration stratum was estimated from visual data collected during the simultaneous visual and acoustic surveys between Oct 17-24, as well as during additional transects completed outside this time window ("Calibration2"). The acoustic data in the Calibration stratum was not used because the acoustic estimate of abundance in this stratum was equal, by design for estimating g_a, to the first visual Calibration estimate. The total estimate for the Calibration was the average of the 2 estimates, weighted by the area surveyed during each period.

$$\begin{aligned}
\hat{N}_{CAL} &= \frac{\mathrm{W}_v \mathrm{L}_{v,CAL}}{\mathrm{W}_v \mathrm{L}_{v,Cal} + \mathrm{W}_v \mathrm{L}_{a,Cal2}} \cdot \frac{n_{v,Cal} \hat{s} \mathrm{A}_{CAL}}{2\mathrm{W}_v \mathrm{L}_{v,Cal} \hat{p}_v \hat{g}_v} + \frac{\mathrm{W}_v \mathrm{L}_{v,Cal2}}{\mathrm{W}_v \mathrm{L}_{v,Cal} + \mathrm{W}_v \mathrm{L}_{v,Cal2}} \cdot \frac{n_{v,Cal2} \hat{s} \mathrm{A}_{CAL}}{2\mathrm{W}_v \mathrm{L}_{v,Cal2} \hat{p}_v \hat{g}_v} \\
&= \left(\frac{\hat{s}}{2\mathrm{W}_v \hat{p}_v \hat{g}_v} \right) \left(\frac{n_{v,Cal} + n_{v,Cal2}}{\mathrm{L}_{v,Cal} + \mathrm{L}_{v,Cal2}} \right) \mathrm{A}_{CAL} \\
&= \left(\frac{\hat{s}}{2\mathrm{W}_v \hat{p}_v \hat{g}_v} \right) \left(\frac{n_{v,CAL}}{\mathrm{L}_{v,CAL}} \right) \mathrm{A}_{CAL},
\end{aligned}$$

where *Cal* refers to sightings and effort between Oct 17-24, *Cal2* to sightings and effort outside that period, and *CAL* to all data in the Calibration stratum. The area-weighted average of the 2 separate estimates is equal to the estimate based on the total number of sightings and visual effort in the Calibration stratum. The CV was

$$\mathrm{CV}^2(\hat{N}_{CAL}) = \mathrm{CV}^2(\hat{s}) + \mathrm{CV}^2(\hat{p}_v) + \mathrm{CV}^2(\hat{g}_v) + \mathrm{CV}^2(n_{v,CAL}).$$

Abundance in the North and West strata N_N and N_W was estimated from acoustic data, but depended, through g_a, on visual and acoustic data in the Calibration period. For the North stratum and using (2),

$$\begin{aligned}\hat{N}_N &= \left(\frac{\hat{s}}{2\mathrm{W}_a\,\hat{p}_a\,\hat{g}_a}\right)\left(\frac{n_{a,N}}{\mathrm{L}_{a,N}}\right)\mathrm{A}_N \\ &= \left(\frac{\hat{s}}{2\mathrm{W}_v\,\hat{p}_v\,\hat{g}_v}\right)\left(\frac{n_{a,N}}{\mathrm{L}_{a,N}}\right)\left(\frac{n_{v,Cal}\mathrm{L}_{a,Cal}}{n_{a,Cal}\mathrm{L}_{v,Cal}}\right)\mathrm{A}_N\,,\end{aligned}$$

where the third term was a "calibration factor" between visual and acoustic data estimated from the Calibration data. The CV of this estimator was

$$\mathrm{CV}^2(\hat{N}_N) = \mathrm{CV}^2(\hat{s})+\mathrm{CV}^2(\hat{p}_v)+\mathrm{CV}^2(\hat{g}_v)+\mathrm{CV}^2(n_{a,N})+\mathrm{CV}^2(n_{v,Cal})+\mathrm{CV}^2(n_{a,Cal})\,,$$

where the last 2 terms show the additional variance due to estimation of the calibration factor.

Abundance in the Central stratum N_C was estimated by a combination of visual and acoustic data, weighted by area surveyed by each method.

$$\begin{aligned}\hat{N}_C &= \frac{\mathrm{W}_v\,\mathrm{L}_{v,C}}{\mathrm{W}_v\mathrm{L}_{v,C}+\mathrm{W}_a\mathrm{L}_{a,C}}\cdot\frac{n_{v,C}\,\hat{s}\,\mathrm{A}_C}{2\mathrm{W}_v\mathrm{L}_{v,C}\,\hat{p}_v\,\hat{g}_v}+\frac{\mathrm{W}_a\,\mathrm{L}_{a,C}}{\mathrm{W}_v\mathrm{L}_{v,C}+\mathrm{W}_a\mathrm{L}_{a,C}}\cdot\frac{n_{a,C}\,\hat{s}\,\mathrm{A}_C}{2\mathrm{W}_a\mathrm{L}_{a,C}\,\hat{p}_a\,\hat{g}_a} \\ &= \left(\frac{\hat{s}}{2(\mathrm{W}_v\mathrm{L}_{v,C}+\mathrm{W}_a\mathrm{L}_{a,C})}\right)\left(\frac{n_{v,C}}{\hat{p}_v\,\hat{g}_v}+\frac{n_{a,C}}{\hat{p}_a\,\hat{g}_a}\right)\mathrm{A}_C \\ &= \left(\frac{\hat{s}}{2\hat{p}_v\,\hat{g}_v}\right)\left(\frac{n_{v,C}+n_{a,C}\dfrac{\mathrm{W}_a}{\mathrm{W}_v}\left(\dfrac{n_{v,Cal}\mathrm{L}_{a,Cal}}{n_{a,Cal}\mathrm{L}_{v,Cal}}\right)}{\mathrm{W}_v\mathrm{L}_{v,C}+\mathrm{W}_a\mathrm{L}_{a,C}}\right)\mathrm{A}_C\,.\end{aligned}$$

The total estimate of abundance was estimated as the sum of the stratum estimates. The stratum estimates were not independent because they shared common terms, particularly p_v, g_v and s. Therefore, the variance of the total estimate was less than the sum of the variances of the stratum estimates. (Appendix to be added)

Comparison with 1997 abundance

We estimated the change in vaquita abundance between 1997 and 2008 in two ways, using Bayesian methods. First, we estimated the change in total abundance. Let N_{1997} be vaquita abundance in 1997, and d the difference in abundance between 1997 and 2008, so that abundance in 2008 = $N_{1997} + d$. Values of $d > 0$ indicated an increase in abundance, while values of $d < 0$ indicated a decrease. We assumed uniform priors for N_{1997} and d. We also assumed that the 1997 and 2008 estimates were independent, although the visual parts of the total estimates in each year shared a common estimate of trackline detection probability. The joint likelihood was

$$Lognormal(N_{1997}; 567, 266)\cdot Lognormal(N_{1997}+d; 250, 109)\,,$$

where $Lognormal(x; a,b)$ was the lognormal probability density of x given mean a and standard deviation b, 567 and 266 were the 1997 estimate and its SE, and 250 and 109

were the 2008 estimate and its SE. The marginal posterior distribution of *d* was obtained by numerical integration of the joint posterior over N_{1997}.

Second, we estimated the change in abundance in the central area of vaquita distribution where 95% of sightings have occurred. In 1997 and 2008, the same area (the Core Area defined in Jaramillo-Legorreta *et al.* 1999) was surveyed by the same vessel (*David Starr Jordan*) using identical methods. The change in abundance within this area should therefore be a good indication of the trend of the population, assuming that there has been no shift in distribution. We used a simple form of a Bayesian line-transect analysis (Eguchi and Gerrodette 2009) to estimate the joint posterior distribution of ESWs, abundance and change in abundance. ESWs and densities were estimated for each year using noninformative priors and half-normal detection functions with no covariates. Effort was 514km in 1997 and 872km in 2008, and the number of sightings, 88 in each year, was assumed to be binomially distributed. Mean group sizes (1.89 in 1997, 1.86 in 2008) were treated as fixed. The informative prior for g_v was a beta(4.5,3.38) distribution with mean 0.571, based on the results of two independent observer teams (Jaramillo-Legorreta *et al.* 1999). The parameter of interest was again *d*, the change in abundance in the central area over the 11-year period, obtained by integrating the joint posterior distribution over the other 4 parameters. The analysis was carried out in R (R Development Core Team 2009) using direct computation of priors, likelihoods and posteriors at regular intervals in a 5-dimensional space. Code is available from the first author on request.

Results

Transects by both vessels achieved reasonably uniform coverage of the strata they sampled (Fig. 2). There was a total of 88 vaquita sightings within 4km of the trackline on 1030.9 km of effort in conditions of Beaufort ≤ 2 (Table 1). There was a total of 29 acoustic detections with perpendicular distances < 450m. Only 4 of these detections, however, occurred on 448.9 km of transect effort in the strata (Table 1). Most acoustic detections occurred during transit to and from the planned transects (Fig. 2).

A half-normal detection function with Beaufort as a covariate was selected for the visual data (Fig. 3A). The estimated effective strip half-width (ESW) was 2.084 km ($f(0)$ = 0.480 km^{-1}). A half-normal function without a Beaufort covariate, a half-normal function with cosine adjustments, and a hazard-rate function all estimated similar ESWs but had AIC differences of +1.5, +2.0, and +3.0, respectively. A half-normal model with no covariates or adjustments fit the perpendicular distances of the 29 acoustic detections reasonably well (Fig. 3B), with ESW = 0.253 km ($f(0)$ = 3.95 km^{-1}). A hazard-rate function estimated a similar acoustic ESW but with an AIC difference of +1.3. The average of the visual and acoustic detection functions were $\hat{p}_v$ = 0.521 (CV = 7.7%) and $\hat{p}_a$ = 0.562 (CV = 15.6%), respectively.

Group sizes of the 88 sightings ranged from 1 to 10, with mean 1.86 and frequencies 32,42,0,11,0,1,0,1,0, and 1. Of the 29 acoustic detections, only one was a pair of click trains that could be interpreted as a pair of animals. If vaquita group sizes in areas surveyed acoustically were the same as in areas surveyed visually, then many of the single acoustic detections represented groups of animals. To estimate abundance, we

assumed that group size of acoustic detections was the same as visual detections. There was no significant relation between visual group sizes and detection probability or distance from trackline, so the mean of observed group sizes was used as expected group size for abundance estimation. Thus, $\hat{s}$ = 1.86 (CV = 5.1%).

During the 8 days the two vessels conducted simultaneous surveys, there were 28 visual detections in 164.8km of effort and 2 acoustic detections in 132.0km of effort (Table 1). g_a was estimated to be 0.419 with CV = 82.3%.

Estimates of abundance ranged from 116 in the East stratum to 0 in the West (Table 2). Vaquita density was highest in the Calibration and East strata, with estimates of 0.092km^{-2} and 0.059km^{-2}, respectively. Estimated density in the North stratum was nearly as high, but this estimate was highly undertain, based on a single acoustic detection. The estimated numbers of vaquitas in the Calibration area for the visual and acoustic data were equal by design, because the acoustic estimate included g_a factor estimated as a ratio with the visual estimate during the 8-day calibration effort. Based on the visual data during the calibration period and outside this period, 57 vaquitas were estimated to be in the Calibration stratum.

The estimates in the East and Calibration strata were based on the intensive visual transect effort. These estimates had CVs around 40%, with most of the variance due to uncertainty in the estimate of g_v. There were no sightings in the Central stratum, despite good visual survey coverage. The acoustic estimate of abundance in the Central stratum was 36, based on a single detection. The combined estimate of 3 vaquitas in the Central stratum was heavily weighted by the visual estimate of no vaquitas, since the visual survey covered a much larger area. The estimate of abundance in the Central stratum was highly uncertain with a CV of 132%. In the West stratum, there were no acoustic detections on the planned tracklines, so the estimate of abundance was zero. However, vaquitas were detected acoustically in the West stratum during transit (Fig. 2). In the North stratum, there were an estimated 74 vaquitas, based on a single acoustic detection. This estimate was also highly uncertain, with a CV of 132% and a 95% confidence interval from 10 to 528. Total 2008 vaquita abundance was estimated to be 250, with a CV of 43.5% and a 95% confidence interval from 110 to 564 vaquitas.

Within the Refuge Area, there were an estimated 123 vaquitas with CV = 34.8% (Table 2), based 71 sightings in 568.9km of effort. We therefore estimated that 0.492 (123/250) of the vaquita population was within the Refuge Area, with a CV of 55.7% for the estimate of this fraction using the delta method. The Option 2 area included 31% of the area of the North stratum (Fig. 1). We estimated that 199 vaquitas, or 0.794 of the total population, were inside the Option 2 area, with a CV of 52.0% for the estimate of this fraction.

The 2008 estimate was 44% (250/567) of the 1997 estimate, a decrease which would be produced by a 7.4% per year rate of decline over the 11-year period. Both estimates had large CIs which included or nearly included the other point estimate (Fig. 4A). The posterior distribution of the change in total abundance between 1997 and 2008 had a mode of -207, a mean of -315, a median of -275, and 90.6% of the probability mass < 0 (Fig. 4B). In other words, the probability that the total population decreased between 1997 and 2008 was about 10 times more than that it increased.

For the central area sampled with identical methods in 1997 and 2008, the 2008 estimate was 42% of the 1997 estimate, using the ratio of the modes of the posterior

distributions of 423 and 176 for 1997 and 2008, respectively (Fig. 5A). This decrease would be produced by a rate of decline of 8.0% per year. The posterior distribution of the change in abundance in the central area had a mode of -116, a mean of -144, a median of -136, and >99.999% of the probability mass < 0 (Fig. 5B). In other words, it was virtually certain that the vaquita population was smaller in 2008 than in 1997 in the central area.

Discussion

The 2008 estimate of 250 vaquitas (CV = 44%) was less than half the 1997 estimate of 567 (CV = 51%) (Jaramillo-Legorreta *et al.* 1999). The two point estimates implied a decline of 7.4%/year and a total decline of 56% over the 11-year period. A Bayesian population model combining these two estimates with additional bycatch and acoustic data estimated a 2008 population size of 207 and a 63% decline over this period (Gerrodette and Rojas-Bracho 2010). The 95% CI of the 2008 estimate reported here included the estimate of 150 based on a predicted trend from the last estimate of abundance in 1997 (Jaramillo-Legorreta *et al.* 2007).

The estimates of total abundance for both 1997 and 2008 had relatively low precision because of the low vaquita density and low survey coverage in areas of shallow water (Central, West and North strata in Fig. 1). Given the low precision and the wide overlap in their confidence intervals (Fig. 4A), the two estimates were not "significantly different" as measured by a null hypothesis significance test ($z = 1.03$, $P = 0.30$ with 2-tailed $\alpha = 0.05$). However, significance tests have many difficulties in application and interpretation (Cohen 1994, Johnson 1999, Yoccoz 1991), and Taylor and Gerrodette (1993) showed that such tests have poor ability to detect changes in abundance for the vaquita and other rare species. Bayesian methods directly estimate the probability of a decline and are more informative about changes in population size. Our Bayesian analysis estimated a 91% probability of decline based on the 1997 and 2008 estimates of total population size (Fig. 4B). This is consistent with the results of Jaramillo Legorreta (2008), who estimated an 85% probability of decline based on acoustic monitoring between 1997 and 2007.

In the central part of the vaquita's range (East and Calibration strata in Fig. 1), the estimates of density and abundance were more precise (Fig. 5A). The probability of decline between 1997 and 2008 in the central area was >99.999% (Fig. 5B). Combining data from multiple sources improves the ability to estimate status and trends (Goodman 2004). Gerrodette and Rojas-Bracho (2010) combined vaquita abundance estimates, including the 2008 estimate reported here, with acoustic and bycatch data in a Bayesian population model. They estimated that total vaquita abundance between 1997 and 2008 declined with similarly high probability > 99.999% - *i.e.*, with virtually complete certainty.

When monitoring to detect changes in abundance, the analysis should include factors which affect probability of detection (Link and Barker 2010, MacKenzie *et al.* 2002, Thomas *et al.* 2004). In many marine mammal studies, sighting rates are used as an index of abundance, which does not account for the effect of Beaufort sea state, behavior, or other factors that might differ among occasions and affect the sighting rates. In this study, for example, even though surveys were conducted only in excellent

conditions (Beaufort ≤ 2), sighting rates in the central area declined by only 41% in the central area between 1997 and 2008, while estimated abundance in the central area declined by 58%. The difference was due to better sighting conditions in 2008 -- mean Beaufort sea state was 1.43 in 1997 and 0.93 in 2008. Line-transect analysis adjusts for the difference in sighting conditions by estimating a slightly larger ESW (1.81km in 1997, 2.08km in 2008) in the better conditions. If sighting rates alone had been used to assess change in vaquita abundance, the decline would have been underestimated because the effect of better sighting conditions in 2008 would not have been accounted for.

The 2008 visual line-transect effort was unusually intense, and emphasized how difficult it is to obtain a precise estimate of abundance of a rare species (Taylor and Gerrodette 1993). In most line-transect surveys, the area effectively surveyed is a small fraction, typically 1-10%, of the study area. For the strata covered by the 2008 visual survey (East, Central and Calibration), the area effectively surveyed was (1030.6*2*2.084) = 4295.5 km^2, which is more than 50% larger than the sum of the stratum areas. In other words, during the 2008 visual survey, each point was sampled more than once on average. The probability of detecting a group of vaquitas at each point was 0.571 ($\hat{g}_v$), which meant that it was probable that some individual vaquitas were sighted more than once. This was simply a consequence of the intensive sampling, and was perfectly valid statistically. The intensive visual sampling in 2008 produced the most precise estimate of vaquita abundance yet achieved.

Acoustic methods are increasingly used in marine mammal studies, both to supplement visual line-transect surveys (Barlow and Rankin 2007) and to monitor activity and trends directly from frequency of vocalizations from fixed hydrophones (Carstensen *et al.* 2006). The acoustic ESW estimated for the vaquita in this study (253m) was larger than the ESW estimated with similar equipment during acoustic surveys for harbor porpoises in the North Sea (208m, Swift *et al.* 2006). One of the obstacles to using acoustic data for abundance estimation has been that the probability of detecting animals acoustically on the trackline, g_a, has not been known (Akamatsu *et al.* 2007). Here an acoustic trackline detection probability was estimated for the first time for phocoenids, based on simultaneous acoustic and visual surveys. The value was low (0.42) and had low precision (CV = 82%). Acoustic detection of vaquitas near the trackline was not certain possibly because (a) vaquitas did not vocalize all the time, (b) the directional high-frequency click was not be aimed at the hydrophone and hence not detected, or (c) a combination of these factors.

With one exception, the click train of each acoustic detection appeared to be from a single individual. Group sizes from visual sightings were considerably different, with a mean of 1.9 and only about 1/3 of the sightings being of single animals. These results indicated that either (1) vaquitas in the acoustically surveyed areas never (or almost never) occurred in groups, or (2) when the hydrophone passed a group of vaquitas, only one of the animals from the group would (usually) be detected. Given the directional nature of porpoise clicks, and data indicating incomplete acoustic detection on the trackline, the second assumption seemed more reasonable. We based our acoustic estimates of abundance on the assumption that acoustic detections represented vaquitas of the same mean group size as visual detections.

All abundance estimates based on acoustic data in this study had low precision (CVs around 130%, Table 2). This was due to both the low number of acoustic

detections on effort, leading to a high CV for the encounter rate, and to the low precision of the estimate of g_a. In the North stratum, for example, a single acoustic detection led to an estimate of 74 vaquitas. The area effectively surveyed acoustically was 170.5*2*0.253/1430.1 or 6% of the area. While this fraction was small, it was estimated with reasonable precision (CV = 15.6% for the acoustic ESW), and group size was also precise (CV = 5.1%). Encounter rate and g_a, on the other hand, had CVs of 100% and 82%, respectively. Any future acoustic surveys should strive to estimate g_a more precisely, and to increase trackline effort so that estimates of abundance are not based on so few detections.

In this study the estimate of g_a was based on the ratio of simultaneous visual and acoustic abundance estimates (Eq. x). Therefore, the information to estimate g_a is contained in other parameters, and the estimators of abundance for each stratum do not contain g_a or p_a. This has the interesting consequence that acoustic perpendicular distances were not needed in this study, nor an estimate of acoustic trackline detection probability. Nevertheless they have their own intrinsic interest so we report their estimates here.

The vaquita conservation plan (SEMARNAT 2008) proposed three options for possible closure to gillnet fishing. Gerrodette and Rojas-Bracho (2010) estimated the probability of success, defined as a population increase from 2008 to 2018, of these protected area options. Among other factors, the probability of success depended on the fraction of the vaquita population that would be protected by each option. Here we estimated those fractions as 0.49 (CV=56%) for Option 1 (the current Refuge Area) and 0.79 (CV=52%) for the larger area of Option 2 (Fig. 1). Because these areas are so small, and vaquitas can swim from one end of their range to the other in a few hours, we believe that vaquitas move throughout their range, and that an individual vaquita will move in and out of a protected area. In other words, we consider these fractions to be estimates of the mean proportion of vaquitas that would be outside the protected areas at any moment in time. Thus, the existing Vaquita Refuge Area protects approximately 50% of the vaquita population, and Option 2 of the vaquita conservation plan, if adopted, would protect approximately 80% of the population. Gerrodette and Rojas-Bracho (2010) estimated that, unless vaquita bycatch is reduced further by expanding the area where gillnet fishing is banned or by developing alternative gear that reduces vaquita bycatch, the vaquita population will probably continue to decline. The results of the present study indicated that the vaquita population declined by more than 50% between 1997 and 2008, an important factor to consider for the implementation of the vaquita conservation plan.

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Table 1. Area, effort and number of vaquita detections, by stratum and data type, used in the estimation of vaquita abundance in 2008.

Stratum	Area in km^2 (A)	Effort in km (L)		Number of detections (*n*)	
		Visual	Acoustic	Visual	Acoustic
Calibration	612.86	164.8	132.0	28	2
Calibration2	612.86	174.3		12	
Central	165.60	57.0	39.9	0	1
East	1959.72	634.8		48	
West	473.51		106.5		0
North	1430.10		170.5		1
Total	4641.79	1030.9	448.9	88	4

Table 2. Estimates of 2008 vaquita abundance (N) and density (D, per km^2), with measures of precision. CV = coefficient of variation, L95 and U95 = lower and upper limits of the 95% lognormal confidence interval. Combined estimates are weighted averages of the stratified visual and acoustic estimates, and the total estimate is a sum of the combined estimates (see text for details). Acoustic estimates include the acoustic trackline detection probability g_a estimated by comparison with the visual estimate in the Calibration area; thus estimated visual and acoustic abundance in the Calibration area was equal by design.

Type	Stratum		Estimate	CV (%)	L95	U95
Visual	Calibration	N	82	40.0	38	174
	Calibration2	N	33	47.0	14	79
	East	N	116	38.2	56	239
	Central	N	0			
	Refuge	N	123	34.8	64	239
Acoustic	Calibration	N	82	110.9	14	479
	Central	N	36	131.6	5	267
	West	N	0			
	North	N	74	129.0	11	511
Combined	Calibration	N	57	40.7	26	122
		D	0.092	40.7	0.043	0.199
	East	N	116	38.2	56	239
		D	0.059	38.2	0.029	0.122
	Central	N	3	129.0	1	18
		D	0.016	129.0	0.002	0.111
	West	N	0			
		D	0			
	North	N	74	129.0	11	511
		D	0.052	129.0	0.007	0.357
Total		N	250	43.5	110	564

Figure captions

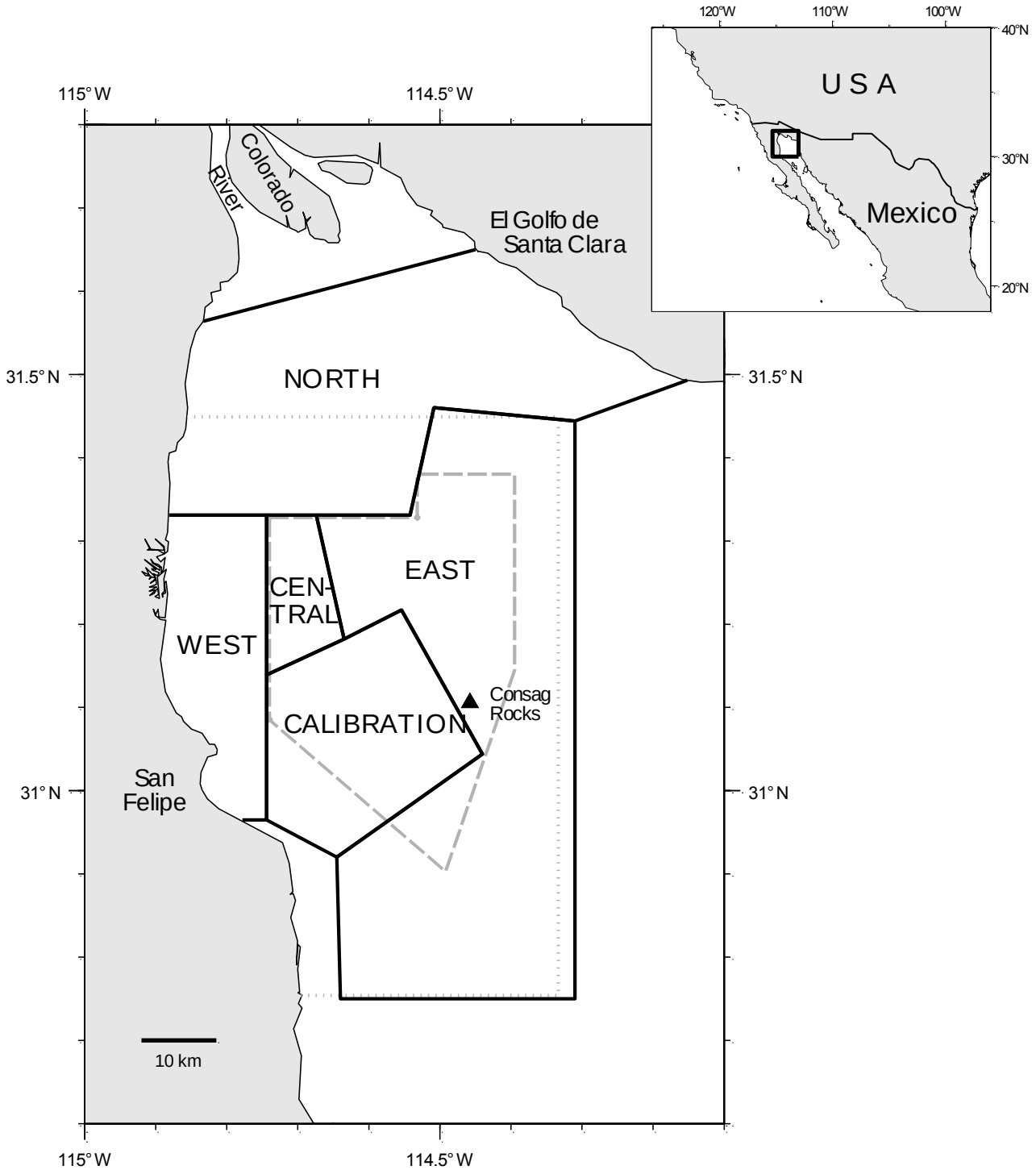
Fig. 1. Study area in the northern Gulf of California, Mexico, with strata used for estimation of vaquita abundance in 2008. Two areas proposed for gillnet fishing closure under the vaquita conservation plan are shown with gray lines. The dashed gray line is the boundary of Option 1 (the Refuge Area for the Protection of the Vaquita), and the dotted gray line is the boundary of Option 2.

Fig. 2. Transects (dark lines) and vaquita detections (circles) for (A) visual transects and (B) acoustic transects used for abundance estimation. Strata are shown as gray lines. X's show additional off-effort vaquita detections not used for abundance estimation.

Fig. 3. Half-normal detection functions and histogram of perpendicular distances for (A) 88 visual detections with Beaufort sea state as a covariate and (B) 29 acoustic detections. Detection probabilities include estimated trackline detection probabilities g_v and g_a.

Fig. 4. Comparison of total vaquita abundance in 1997 and 2008. (A) Point estimates with 95% lognormal confidence intervals. (B) Marginal posterior distribution of change in total abundance between 1997 and 2008. Gray line is the prior distribution of change in abundance. Negative values indicate a smaller population in 2008, and the dashed vertical line at 0 helps to visualize the cumulative probability that the vaquita population increased or decreased between 1997 and 2008.

Fig. 5. Comparison of vaquita abundance in a common central study area in 1997 and 2008. (A) Marginal posterior distributions of abundance (central 95%) for each year. Black horizontal lines are medians, and widths of polygons are proportional to probability. (B) Marginal posterior distribution of change in abundance in the central area between 1997 and 2008. Gray line is the prior distribution of change in abundance. Negative values indicate a smaller population in 2008.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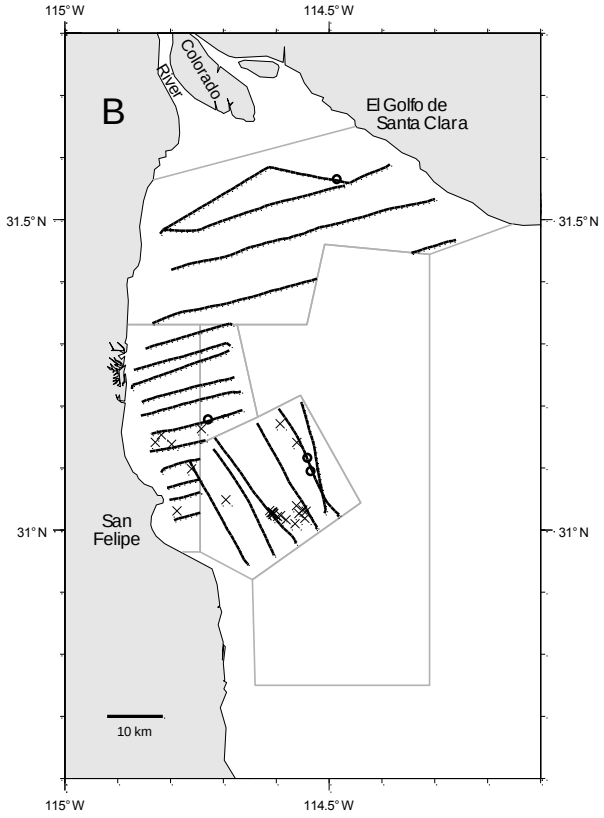
110°W
100°W
40°N
30°N
20°N
U S A
Mexico
115° W
114.5° W
Colorado
River
El Golfo de
Santa Clara
31.5° N
NORTH
EAST
CEN-
TRAL
WEST
CALIBRATION
Consag
Rocks
San
Felipe
31° N
10 km

Fig. 1.

A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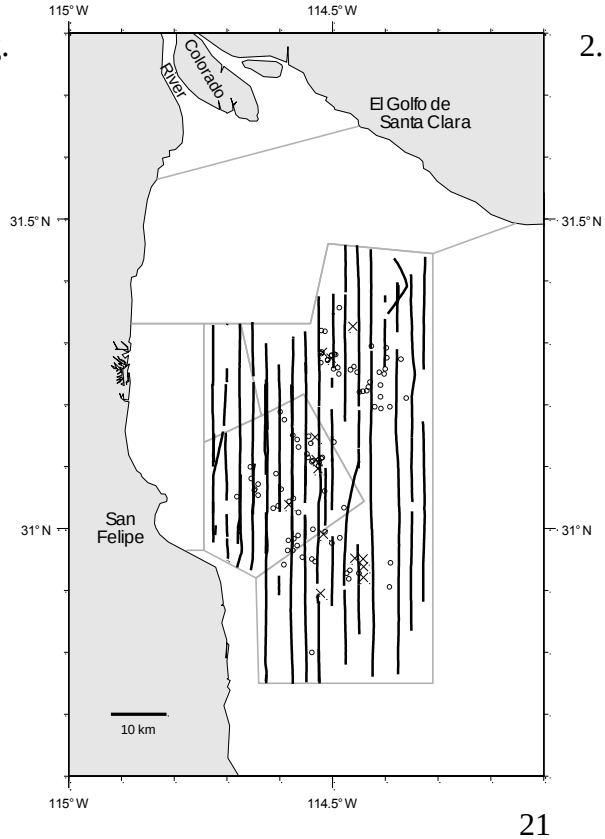
114.5° W
Colorado River
B
El Golfo de Santa Clara
31.5° N
31° N
San Felipe
10 km

Fig. 2.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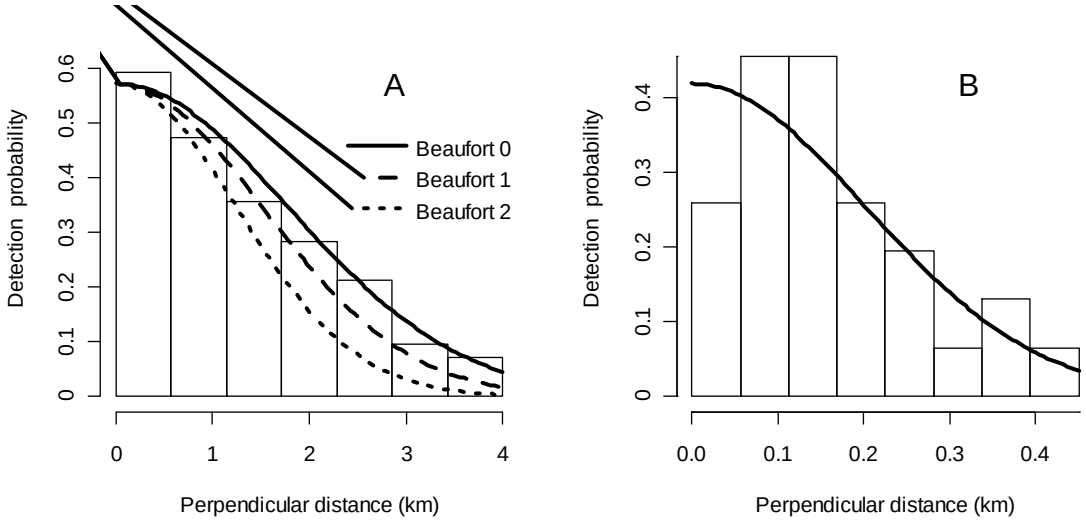
31.5° N
31° N
San Felipe
10 km


A
Beaufort 0
Beaufort 1
Beaufort 2
Detection probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
Perpendicular distance (km)
B
Detection probability
0
0.1
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0.2
0.3
0.4
Perpendicular distance (km)

Fig. 3.

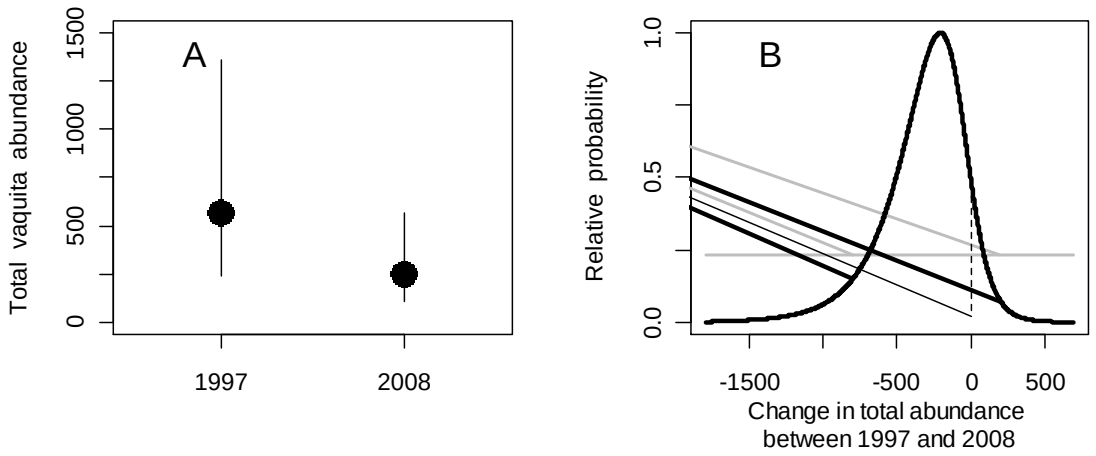
A
Total vaquita abundance
0
500
1000
1500
1997
2008
B
Relative probability
0.0
0.5
1.0
-1500
-500
0
500
Change in total abundance
between 1997 and 2008

Fig. 4

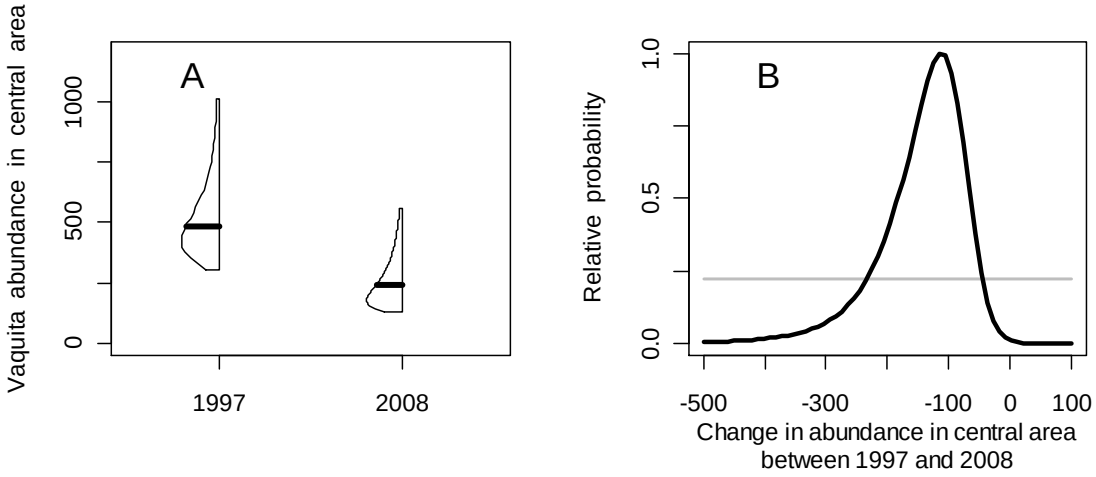
A
Vaquita abundance in central area
0
500
1000
1997
2008
B
Relative probability
0.0
0.5
1.0
-500
-300
-100
0
100
Change in abundance in central area
between 1997 and 2008

Fig. 5