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Estimating the success of protected areas for the vaquita, *Phocoena sinus*

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Abstract

Bycatch in artisanal gill nets threatens the vaquita, *Phocoena sinus*, with extinction. In 2008 the Mexican government announced a conservation action plan for this porpoise, with three options for a protected area closed to gill net fishing. The probability of success of each of the three options was estimated with a Bayesian population model, where success was defined as an increase in vaquita abundance after 10 yr. The model was fitted to data on abundance, bycatch, and fishing effort, although data were sparse and imprecise. Under the first protected area option, the existing Refuge Area for the Protection of the Vaquita, bycatch was about 7% of population size, and probability of success was 0.08. Under the second option with a larger protected area, the probability of success was 0.35. The third option was large enough to eliminate vaquita bycatch and had a probability of success >0.99. Probability of success was reduced if elimination of vaquita bycatch was delayed or incomplete. Despite considerable efforts by the Mexican government to support vaquita conservation, abundance will probably continue to decline unless additional measures to reduce vaquita bycatch are taken, such as banning gill nets within the vaquita's range and developing effective alternative fishing gear.

Key words: Gulf of California porpoise, *Phocoena sinus*, bycatch, conservation plan, Bayesian population model, marine protected area, critically endangered species.

Almost as soon as the vaquita, *Phocoena sinus*, or Gulf of California porpoise, was described 50 yr ago (Norris and McFarland 1958), there were warnings that this small cetacean was vulnerable to fishing nets. Norris and Prescott (1961) reported bycatch in several fisheries in the vaquita's limited range in the northern Gulf of California. Mitchell (1975) remarked that the vaquita's "distribution in gill net fishing zones represents potential management problems." Villa-Ramírez (1976), after noting that knowledge of vaquitas was very limited, stated that "the only point well indicated was that, through the action of man, this species was seriously endangered." Brownell (1983) mentioned the impact of incidental takes by fishing operations. Vidal (1995) documented that 128 vaquitas were killed in fishing nets between 1985 and 1992, and D'Agrosa *et al*. (1995) documented 15 more deaths during 1993–1994. Turk Boyer and Silber (1990) and Vidal (1995) made rough bycatch estimates of 32 and 35 vaquitas/year, respectively. D'Agrosa *et al*. (2000) made the only statistical estimate, 39 vaquitas with a 95% confidence interval from 14 to 93, based on observed fishing trips and interviews with fishermen during 1993 in El Golfo de Santa Clara, one of the two main fishing towns in the range of the vaquita. These authors considered that this estimate represented half the total bycatch for the population.

Given the scarcity of sightings and limited range of the species (Wells *et al.* 1981, Brownell 1986, Silber 1990, Gerrodette *et al.* 1995), researchers recognized that the vaquita population could not be very large. By the late 1990s, estimates based on line-transect surveys indicated that the population was about 500–600 animals (Barlow *et al.* 1997, Jaramillo-Legorreta *et al.* 1999), although the confidence intervals on the estimates were large. While there was considerable uncertainty about both the size of the bycatch and the size of the population, there were strong indications that the annual bycatch in gill nets was large relative to population size and not sustainable. Rojas-Bracho and Taylor (1999) evaluated various factors and concluded that incidental mortality in gill nets was the immediate threat to the existence of the species. D'Agrosa *et al*. (2000) showed that the estimated 1993 mortality was higher than the replacement rate and hence not sustainable.

In 1993 the Mexican government created the Upper Gulf of California and Colorado River Delta Biosphere Reserve ("Biosphere Reserve"), one of whose goals was to protect the vaquita (SEMARNAP 1995). The Biosphere Reserve banned gill net fishing in the "nuclear" area near the mouth of the Colorado River (Fig. 1). In 1997 the government established the International Committee for the Recovery of the Vaquita (CIRVA, from its name in Spanish). CIRVA has met three times and issued reports and recommendations, chiefly to eliminate vaquita bycatch and find economic and fishing alternatives for fishermen (Rojas-Bracho *et al.* 2006). In 2005 an additional Refuge Area for the Protection of the Vaquita ("Refuge Area") covering the central part of the vaquita's range was created (Fig. 1). Gill net fishing in the Refuge Area was officially prohibited, but there was little enforcement and the ban was widely ignored. Recognizing the increasingly dire situation, the International Union for the Conservation of Nature listed the vaquita as "critically endangered," the highest category of threat, on its Red List in 1996. Major scientific organizations, including the Society for Marine Mammalogy, the Society for Conservation Biology, the American Society of Mammalogists and the International Whaling Commission, have sent official letters to the Mexican government urging action to prevent further decline and possible extinction.

In response to these appeals, to the announcement of the likely extinction of the baiji, *Lipotes vexillifer* (Turvey *et al.* 2007), and to the continuing decline of the vaquita (Jaramillo-Legorreta *et al.* 2007; Gerrodette *et al.*, in press), on 30 April 2008, the president of Mexico announced a conservation action plan to prevent extinction of the species (SEMARNAT 2008). We refer to this document by its Spanish acronym PACE Vaquita or simply as the conservation plan. The central goal of PACE Vaquita is to eliminate vaquita bycatch by enforcing the existing bans on gill net fishing in

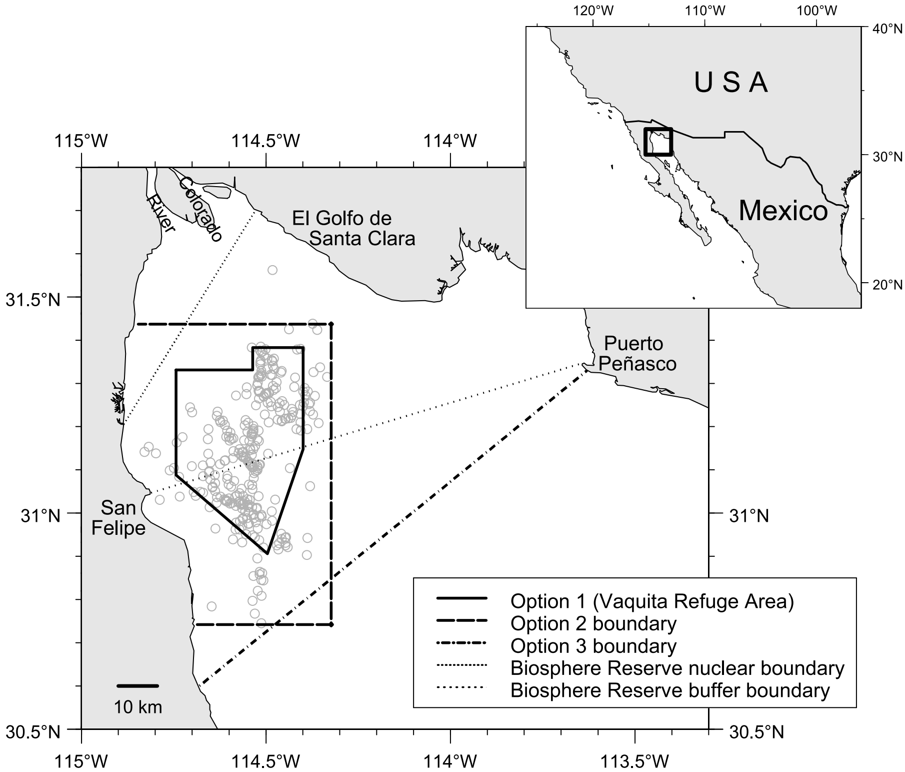

Figure 1. The northern Gulf of California, Mexico, with boundaries of three options for Vaquita Protection Areas closed to gill net fishing proposed under the PACE Vaquita conservation plan. Boundaries of the Upper Gulf of California and Colorado River Delta Biosphere Reserve are also shown. When a boundary is shown, the associated water area is to the north and/or west. Definite vaquita sightings or acoustic detections from 1993, 1997, and 2008 are shown as gray circles.

the Refuge Area and the nuclear Biosphere Reserve, possibly expanding the ban to a larger protected area, encouraging methods of fishing that do not catch vaquitas, and providing economic compensation to fishermen through a buyout plan and assistance with starting alternative businesses.

PACE Vaquita began to be implemented in 2008. A voluntary buyout program substantially reduced the number of gill net boats, and the ban on gill net fishing in the Refuge Area was effectively enforced for the first time during the 2008 shrimp season.[1] For the future, PACE Vaquita described three options of different areas that might be closed to gill net fishing. The conservation plan described the economic impacts of the three scenarios on fishermen, and an associated report evaluated the plan in terms of its socioeconomic objectives (Arellano Gault *et al.* 2008). Neither document, however, described the biological consequences of the different options for

[1]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Áreas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico D.F., December 2008.

vaquitas, nor estimated how effective the different options would be for preventing further decline of the species. Furthermore, besides the decision about which area to close to gill net fishing, other critical details of the conservation plan remain to be decided, such as how soon the plan will be implemented, and how the ban on gill net fishing will be enforced effectively.

Globally, bycatch in fishing gear is an important threat to cetaceans (Reeves *et al.* 2003, Read *et al.* 2006). The effects of incidental fishing mortality on the vaquita are magnified because of the species' small population size and limited range. Marine-protected areas (refuges, reserves, sanctuaries, parks, *etc*.) can be effective methods of protecting diversity and guarding against overfishing. Some protected areas have been specifically designated for cetaceans (Hoyt 2005), which can be effective to protect critical habitat (Hooker *et al.* 1999, Cañadas *et al.* 2005) or to mitigate a particular threat such as bycatch (Dawson *et al.* 2001). Mexico established the world's first whale sanctuaries in 1972 to protect the breeding lagoons of the gray whale, *Eschrichtius robustus*, which contributed to the recovery of the species (Urbán-Ramírez *et al.* 2003, Jones and Swartz 2009). While it is important to determine if existing conservation plans are working (Kleiman *et al.* 2000), it is also important to attempt, at the outset of a plan, to predict its success in order to select the best options. Because banning gill net fishing will affect fishermen economically, it is important to estimate the probable success of various scenarios in the vaquita conservation plan. Slooten (2007) and Slooten and Dawson (2009) used simulations to assess the effectiveness of measures aimed at reducing the bycatch of Hector's dolphin, *Cephalorhynchus hectori*.

We used a population model fitted to data to evaluate whether PACE Vaquita will result in an increase in vaquita abundance. Specifically, we used Bayesian methods (1) to estimate the success of immediate (2010) implementation of each of the three proposed protected areas, and (2) to estimate the consequences of delayed or partial implementations of the plan's goal of eliminating vaquita bycatch. We also used the model to estimate how effective the Biosphere Reserve and the Refuge Area have been as protected areas for the vaquita prior to the conservation plan. The political, social, and economic mechanisms by which the reduction in vaquita bycatch will be achieved under PACE Vaquita are critically important to the success of the plan, but these topics are beyond the scope of this paper.

Methods

Definition of Success

As a metric of the success of actions taken under PACE Vaquita, we used the ratio of vaquita population sizes in 2008, at the initiation of the conservation plan, and 2018, 10 yr later. We chose 10 yr because that was long enough for differences among the scenarios described below to be expressed, but short enough to be politically relevant. Thus we defined

$$R_{PACE} = N_{2018}/N_{2008},$$

where N_t was vaquita population size in year t. $R_{PACE} > 1$ indicates that the management actions taken under the conservation plan will be successful (*i.e.*, the vaquita population will be larger in 2018), while $R_{PACE} < 1$ indicates that they will not. Similarly, as measures of how effective the existing Biosphere Reserve and the

Refuge Area have been for vaquitas prior to the conservation plan, we defined

$$R_{reserve} = N_{2008}/N_{1993}$$

and

$$R_{refuge} = N_{2008}/N_{2005},$$

where 1993 and 2005 were the years when the Biosphere Reserve and Refuge Area were established, respectively.

We are uncertain of the values of R_{PACE}, $R_{reserve}$, and R_{refuge} because we are uncertain of the values of N_{1993}, N_{2005}, $N_{2008,}$ and N_{2018}. The statistical problem is to estimate R_{PACE} and other quantities, given available data. Of particular interest is the probability of success $P(\text{success}) \equiv P(R_{PACE} > 1)$, that is, the probability that actions under the conservation plan will lead to an increase in the number of vaquitas by 2018.

Population Model

Because current vaquita abundance has been estimated to be <10% of its historical level (Jaramillo-Legorreta 2008) and bycatch is the main factor affecting vaquita population size (Rojas-Bracho and Taylor 1999), a simple model of population dynamics was

$$N_t = N_{t-1}\, e^{r} - B_t, \tag{1}$$

where N_t was the number and B_t the bycatch of vaquitas in year t, and r was the population growth rate due to natural birth and death processes in the absence of bycatch. According to this model, each year the vaquita population increases by a number of animals proportional to its current size, but decreases by the number of animals taken as bycatch. Abundance is measured after these processes. The model was density-independent; the vaquita population was assumed to be sufficiently far from carrying capacity that the population would, for the time period considered here, grow exponentially at rate r in the absence of bycatch.

The intrinsic population growth rate for vaquitas was not known, so r was treated as a parameter to be estimated with an informative prior from the literature. We estimated N_t from 1993 to 2018, because 1993 was the year the Biosphere Reserve was established. The initial population size, N_{1992}, was a second parameter to be estimated.

Vaquita bycatch B_t for each year was not known. In the range of the vaquita, there are several seasonal gill net fisheries with different vaquita bycatch rates (D'Agrosa *et al.* 2000). Fishing is carried out by two to three men in open fiberglass boats with outboard motors, locally called *pangas*. We assumed the probability that a vaquita encountering a gill net would be killed was constant across years. The number of encounters between vaquitas and gill nets depended on the density of both vaquitas and boats. Thus we modeled bycatch in year t for $t < 2008$ as

$$B_t = q\,\frac{P_t N_{t-1}}{A}, \tag{2}$$

where P_t was the number of pangas in year t in area A where vaquitas occur, and q was a parameter to be estimated. The vaquita bycatch rate q included all the factors that converted the number of pangas into an annual bycatch rate, such as the fraction of pangas that were active, the fraction of active pangas that fished on a given day, the fraction of days in a year when fishing was allowed, and the probability that a vaquita was caught given that a panga was fishing.

The annual number of pangas P_t was not known exactly. Records of the number of registered pangas and permits were incomplete; in addition, there was a substantial amount of fishing by unregistered boats. To include uncertainty in the amount of fishing effort, let b be the proportional uncertainty in the number of pangas. Thus, if X was the reported number of pangas in a given year, we modeled the actual number of pangas, including uncertainty, as $X(1 + b)$, where b was a parameter to be estimated. In 1993 there were reported to be 500 pangas from the towns of San Felipe and El Golfo de Santa Clara (Vidal 1995). We did not include pangas from Puerto Peñasco, only a small number of which fish in the range of the vaquita (Fig. 1). By 2007 the number of pangas had increased to 837.[2] If fishing effort increased steadily between 1993 and 2007, the number of pangas fishing in the range of the vaquita, including uncertainty, can be expressed as

$$P_t = \left[500 + 337\left(\frac{t - 1993}{2007 - 1993}\right)\right] \ (1 + b),$$

for each year t from 1993 to 2007. In 2008 and 2009 the number of pangas was reduced to 819 and 589, respectively[3] as PACE Vaquita began to be implemented.

Scenarios

PACE Vaquita described (pp. 44–47) three areas for possible closure to gill net fishing. We refer to each as a Vaquita Protection Area (VPA) to distinguish them from the existing Refuge Area and Biosphere Reserve. VPA Option 1 was the Refuge Area, VPA Option 2 was a larger area that included most vaquita sightings and acoustic detections, and VPA Option 3 was an area that included the current known range of the species (Fig. 1). To predict how effective these options would be, we estimated R_{PACE} for each, assuming no vaquita bycatch within a VPA (*i.e.*, perfect enforcement). We also estimated R_{PACE} under scenarios of delayed implementation, in which elimination of vaquita bycatch occurred after some years rather than immediately in 2010. Finally, we estimated R_{PACE} under scenarios of partial implementation, in which some vaquita bycatch continued instead of being eliminated completely. Partial implementation could occur if the buyout were not complete, if the fishing ban in the VPAs were not completely enforced, or if there were unauthorized fishing by unregistered boats.

[2]Rojas-Bracho, L., A. Jaramillo-Legorreta and G. Cárdenas-Hinojosa. 2009. Número de embarcaciones menores tipo "panga" en el Alto Golfo de California. CICMM-INE unpublished report. 6 pp.

[3]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Áreas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico D.F., 6 July 2009.

Vaquita Protection Areas in PACE Vaquita

The effectiveness of a protected area depends on its size, the quality of its habitat for the species of concern, and the degree to which it reduces threats to the population. In the case of the vaquita, the total range of the species is so small that animals can move throughout the area within a day or even within a tidal cycle (Jaramillo-Legorreta 2008). Therefore, we assumed that vaquitas would move freely in and out of VPA Options 1 and 2 (Fig. 1). Option 3 was assumed to include the whole range of the species. We assumed that, following the establishment of a VPA, vaquita distribution would not change but fishing effort would. Fishing effort previously inside the VPA might simply be displaced outside, leading to a higher concentration of gill nets, and higher vaquita bycatch, outside the VPA. However, some of the fishing effort previously inside the VPA might go away, because of buyout offers or because fishermen decide to retire, fish less often, or fish elsewhere. Option 1, the existing Refuge Area, effectively began in 2008 and continued in 2009, so the redistribution of fishing effort has already occurred. For Option 2, we assumed, optimistically from the conservation point of view, that none of the fishing effort currently in this area would continue if this VPA were established. We assumed that Option 2 or 3, if implemented, would begin in 2010, and that the ban on gill net fishing in these areas would be strictly enforced.

To model vaquita bycatch for each VPA option, we modified Equation 2 to estimate a new density of gill nets and vaquitas, based on the fractions of vaquita range, vaquita abundance and fishing effort that would occur outside the protected area. Thus if fraction f_N of total abundance N was inside a VPA, the number of vaquitas exposed to the risk of bycatch outside the VPA was $N(1 - f_N)$.

Option 1

The area of Option 1 was 27.2% of the 2008 survey area described in Gerrodette *et al*. (in press), which we assumed covered the whole range of the species. Let f_{N_1} be the probability that a vaquita is inside the Option 1 area. Then vaquita bycatch under Option 1 was modeled as

$$B_t = q \frac{P_t N_{t-1}}{A} \frac{(1 - f_{N_1})}{(1 - 0.272)},$$

for $t \geq 2008$, where f_{N_1} was a parameter to be estimated.

Option 2

The area of Option 2 was 77.1% of the 2008 survey area. Let f_{N_2} be the probability that a vaquita is inside the Option 2 area. Additionally, let f_P be the fraction of fishing effort that occurs inside the Option 2 area. On the assumption that this fishing effort would not continue, fishing effort outside the Option 2 area would be a fraction $1 - f_p$ of the previous effort. Therefore, bycatch for Option 2 was modeled as

$$B_t = q \frac{P_t N_{t-1}}{A} \frac{(1 - f_{N_2})\big(1 - f_P\big)}{(1 - 0.771)},$$

for $t \geq 2010$, where f_{N_2} and f_P were additional parameters to be estimated.

Option 3

We assumed that Option 3 would include the entire vaquita population ($f_{N_3} = 1$), and thus have no bycatch beginning in 2010.

Delayed or Partial Implementation

We considered several scenarios of delayed or partial implementation of the conservation plan. For these scenarios, we assumed that the ban on gill net fishing in the existing Refuge Area would continue to be enforced, and that delayed or partial implementation applied to areas outside the Refuge Area. For scenarios of delayed implementation, we assumed that gill net fishing effort P_t would remain at the 2009 level until the year the plan was fully implemented and vaquita bycatch ended. For scenarios of partial implementation, we assumed that, beginning in 2010, gill net fishing effort, and thus vaquita bycatch, would be at 10%, 20%, 30%, 40%, 50%, 60%, or 70% of the 2007 level and would continue at that level until 2018.

Data

Data to estimate the parameters of the model were a partial abundance estimate in 1993, a partial estimate of vaquita bycatch in 1993, complete abundance estimates in 1997 and 2008, acoustic detections in 1997 and 2001–2007, estimates of the number of gill net fishing boats in 1993 and 2007–2009, and aerial counts of the number and position of boats on 12 occasions in 2005, 2006, and 2009 (Table 1). In 1997 abundance was estimated in both a core area (approximately the eastern two-thirds of the Option 2 area shown in Fig. 1) and an additional shallow area (Jaramillo-Legorreta *et al.* 1999). To use the partial 1993 estimate in the model, let f_c be the fraction of the population in the core area,

$$f_c = \frac{N_{core}}{N_{total}},$$

where $0 \leq f_c \leq 1$ was a parameter to be estimated. To use the acoustic data, let a be the acoustic detection rate per hour per vaquita, so that

$$\frac{d_t}{h_t} = aN_t, \tag{3}$$

where d_t was the number of acoustic vaquita detections in h_t hours of recording in year t, and $a \geq 0$ was a parameter to be estimated.

Prior Distributions

Bayesian methods were used to estimate the nine parameters of the model (Table 2). Bayesian methods require prior distributions to represent knowledge about the parameters prior to considering the data. We used uniform prior distributions for a,

Table 1. Data and likelihood functions used to fit the vaquita population model. Values for parameters of the gamma and beta functions were calculated from data by methods described in the text. The number of gill net fishing boats was used as an index of fishing effort, and thus used indirectly to fit the model through bycatch and abundance.

Type of data	Year	Estimate (95% CI)	Reference	Likelihood function
Abundance estimate in core area	1993	311 (147, 653)	Barlow *et al*. 1997, Jaramillo-Legorreta *et al*. 1999	Gamma (7.59, 0.021)
Bycatch estimate from El Golfo de Santa Clara	1993	39 (14, 93)	D'Agrosa *et al*. 2000, Table 3	Gamma (5.53, 0.118)
Abundance estimate in core area	1997	409 (105, 912)	Jaramillo-Legorreta *et al*. 1999, Table 1	Gamma (6.60, 0.014)
Abundance estimate in shallow area	1997	158 (20, 655)	Jaramillo-Legorreta *et al*. 1999, Table 1	Gamma (2.57, 0.010)
Abundance estimate in Option 1 area	2008	121 (59, 250)	Gerrodette *et al*., in press; Table 2	Gamma (7.91, 0.057)
Abundance estimate in Option 2 area	2008	195 (66, 575)	Gerrodette *et al*., in press; Table 2	Gamma (3.92, 0.015)
Fraction of fishing effort inside Option 2 area, from aerial counts of boats	2005, 2006, 2009	$\bar{x} = 0.55$ SD $= 0.20$ $n = 12$	García-Caudillo[a]	Beta (3.00, 2.45)
Acoustic detections in core area	1997, 2001–2007	total of 76 in 523 h	Jaramillo-Legorreta 2008, Table II	Poisson ($ah_t N_t$)
Number of gill net fishing boats in vaquita range	1993, 2007–2009	500, 837, 819, 589	Vidal 1995, Rojas-Bracho *et al*. 2009[b] L. Fueyo pers. comm[c]	Index of fishing effort

[a]García-Caudillo, Juan Manuel. 2010. Distribución espacio-temporal del esfuerzo pesquero en el área de distribución de la vaquita marina, *Phocoena sinus*. Unpublished report.

[b]Rojas-Bracho, L., A. Jaramillo-Legorreta and G. Cárdenas-Hinojosa. 2009. Número de embarcaciones menores tipo "panga" en el Alto Golfo de California. CICMM-INE unpublished report. 6 pp.

[c]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Aŕeas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico D.F., 6 July 2009.

Table 2. Parameters of the vaquita population model, with summaries of their prior and posterior distributions. Mode is the value of maximum probability and 95% PI is the interval which includes the central 95% of probability density. For ease of displaying small values, bycatch rate q and acoustic detection rate a are shown per thousand.

Parameter	Description	Source of prior information	Prior distribution	Prior mode (95% PI)	Posterior mode (95% PI)
r	Exponential population growth rate (per year)	Reilly and Barlow 1986, Hohn *et al*. 1996, Moore and Read 2008	Gamma (6,150)	0.033 (0.015, 0.077)	0.038 (0.015, 0.078)
q (×1,000)	Bycatch rate (km^2 per boat per year per vaquita) × 1,000	Fleischer *et al*. 1996	Gamma (1.4, 2,200)	0.18 (0.035, 1.0)	0.17 (0.10, 0.25)
N_{1992}	Population size in 1992 (number of animals)	Barlow *et al*. 1997	Gamma (3.49, 0.004)	623 (209, 1,983)	675 (428, 1,064)
a (×1,000)	Acoustic detection rate (per hour per vaquita) × 1,000	no prior information	Uniform (0, 2)	1.0 (0.05, 1.95)	0.45 (0.29, 0.70)
b	Proportional error in gill net fishing effort	L. Fueyo[a], J. Campoy[b]	Normal (0, 0.1^2)	0 (−0.196, 0.196)	−0.0090 (−0.216, 0.177)
f_c	Fraction of vaquita population inside core area	Barlow *et al*. 1997	Uniform (0, 1)	0.5 (0.025, 0.975)	0.58 (0.32, 0.87)
f_{N_1}	Fraction of vaquita population inside Option 1 area	no prior information	Uniform (0, 1)	0.5 (0.025, 0.975)	0.49 (0.25, 0.72)
f_{N_2}	Fraction of vaquita population inside Option 2 area	no prior information	Uniform (0,1)	0.5 (0.025, 0.975)	0.79 (0.41, 0.92)
f_P	Fraction of gill net fishing effort inside Option 2 area	no prior information	Uniform (0,1)	0.5 (0.025, 0.975)	0.52 (0.16, 0.87)

[a]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Áreas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico, August 2009.

[b]Personal communication from J. Campoy, Av. Jalisco Entre Calle 9 Y 10, Col. Sonora, C. P. 83440, San Luis Rio Colorado, Sonora, Mexico, August 2009.

f_c, f_N, and f_P. The other parameters had some previous data that were included as informative priors.

The prior for bycatch rate q was based on data from an experimental totoaba (*Totoaba macdonaldi*) fishery between 1983 and 1993 in which four vaquitas were killed in 682 observed sets (Fleischer *et al.* 1996). If we assume approximately that each boat fished for totoaba 30 d/yr on average (Cisneros-Mata *et al.* 1995 mentioned that fishing took place from January through April), that each boat made one set per day when fishing, and that vaquita population size during the time of the experimental fishery was 1,000 animals, a rough estimate of prior bycatch rate was $4 \times 30/682/1{,}000 = 0.00018$. Because these were approximate numbers from a different fishery, we treated these prior data as only slightly informative by using a broad gamma(1.4, 2,200) distribution, which had a modal value of 0.00018 but a large variance (Table 2).

The prior for N_{1992} was based on data in Barlow *et al*. (1997), who gave estimates of vaquita abundance of 503, 855, and 572 with coefficients of variation of 0.63, 0.50, and 1.43, respectively, from boat and aerial surveys prior to 1993. Using the inverse of the variances as weights, we computed a weighted abundance of 623 with standard error 467 for these data. The mode and standard deviation of a gamma(3.49, 0.004) distribution matched these values (Table 2).

For the prior distribution of b, uncertainty in the number of pangas, we used an informative normal distribution with mean zero and standard deviation 0.1. This degree of uncertainty implied that although the number of pangas in 2007 was reported to be 837, the (unknown) true number was between 672 and 1002 with probability 0.95. People familiar with the fishery agreed that this range included all reasonable values.[4,5]

Finally, we assumed that a reasonable prior for the population growth rate r was a gamma(6, 150) distribution, which has a mean of 0.040, a mode of 0.033, and a central 95% probability interval from 0.015 to 0.077. A population growth rate of 0.04 is widely used in U.S. marine mammal management (Wade 1998). Rojas-Bracho *et al.* (2006) considered that the maximum possible growth rate for vaquitas was 0.04, but we allowed the possibility of higher growth rates. Jaramillo-Legorreta (2008) estimated a mean vaquita population growth rate of 0.04, but because he used some of the same data in Table 1, we do not use his results as prior information. Moore and Read (2008) estimated a median growth rate of 0.046 (90% probability interval 0.004–0.116) for the related harbor porpoise, *P. phocoena*. Reilly and Barlow (1986) showed that it was highly unlikely that growth rates for delphinids could be as high as 0.109. Given reproductive data that indicated vaquitas might not reproduce annually (Hohn *et al.* 1996), we used a maximum growth rate near 0.08 (Table 2).

[4]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Áreas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico, August 2009.

[5]Personal communication from J. Campoy, Director de la Reserva de la Biósfera del Alto Golfo de California y Delta del Río Colorado, CONANP; Av. Jalisco Entre Calle 9 Y 10, Col. Sonora, C. P. 83440, San Luis Rio Colorado, Sonora, Mexico, August 2009.

Likelihood Functions

The model was fitted to data using the gamma distribution for abundance and bycatch estimates, the Poisson distribution for the discrete acoustic detections, and the beta distribution for the fraction of fishing effort occurring outside the proposed VPAs (Table 1). We assumed the joint likelihood given all the data were the product of the individual likelihoods. Gamma distributions approximated the point abundance estimates and confidence intervals better than normal or lognormal distributions. We chose parameters for the gamma distributions that minimized the sum of the absolute differences between the 95% confidence limits and the 2.5% and 97.5% quantiles of the gamma distributions, conditional on the modes of the gamma distributions being equal to the point estimates. The 1993 and 1997 abundance estimates for the core area were each f_c of the total abundance estimates for their respective years, while the 1997 abundance estimate for the shallow area was $1 - f_c$ of the total. The 2008 abundance estimates for the Option 1 and 2 areas were fractions of the total, f_N inside and $1 - f_N$ outside. The 1993 bycatch estimate from El Golfo de Santa Clara was assumed to be half the total 1993 bycatch, because there were approximately equal amounts of fishing from El Golfo and San Felipe (Vidal 1995). Because the rate of acoustic detections was low (<1/h), and under the assumption that detections were independent on an annual scale, the probability of d_t detections was modeled by a Poisson distribution with mean ah_tN_t (Eq. 3). From counts of gill net fishing boats from a small plane on 12 occasions in 2005, 2006, and 2009, we computed beta parameters 3.00 and 2.45 from the mean and variance (Gelman *et al.* 2004, p.582) of the fraction of fishing effort inside VPA Option 2 (Table 1).

Parameter Estimation

Posterior distributions were calculated using Bayes' theorem,

$$p(\theta|\text{data}) = p(\text{data}\,|\theta)p(\theta) \Big/ \sum\nolimits_{\theta} p(\text{data}\,|\theta)p(\theta),$$

where $p(\text{data}|\theta)$ was the likelihood, $p(\theta)$ the prior, and θ the vector of nine parameters. Prior, likelihood and posterior distributions were obtained from 10^8 independent uniform random samples from the joint parameter space. For each sample of parameter values, prior probabilities were computed with the distributions in Table 2 and likelihoods with the functions in Table 1. Values of quantities of interest, such as R_{PACE}, $R_{reserve}$, R_{refuge}, N_t, and B_t, were calculated for each sample. Although computationally inefficient, this direct approach was adequate for this relatively simple model. The probability density >1.0 and quantiles of the posterior distributions were calculated from the binned cumulative posterior distributions. We reported the interval between the 0.025 and 0.975 quantiles of the marginal posterior distribution as the 95% probability interval (95% PI) for an estimate. All programming, computation, and graphics were carried out in R (R Development Core Team 2009).

Results

The most probable values (posterior modes) for the basic parameters were $r =$ 0.038, $q = 0.00017$, $N_{1992} = 675$, $a = 0.00045$, $b = -0.0090$, $f_c = 0.58$, $f_{N_1} =$

Table 3. Probability of future success of three protected area options proposed in the PACE Vaquita conservation plan, and past success of the Upper Gulf of California and Colorado River Delta Biosphere Reserve ("Biosphere Reserve") and Refuge Area for the Protection of the Vaquita ("Refuge Area"). Success is defined as an increase in vaquita population size during the appropriate time period. Median R_*, where R_* is R_{PACE}, $R_{reserve}$, or R_{refuge}, is the median of the posterior distribution of the ratio of population sizes during the time period (see Methods). $R_* < 1$ indicates a decrease in population size, while $R_* > 1$ indicates an increase. Values of *P*(success) show the probability that the vaquita population will increase (R_{PACE}) or has increased ($R_{reserve}$ and R_{refuge}) for each scenario during the time period shown.

	PACE Vaquita conservation action plan			Biosphere reserve	Refuge area
Time period	2008–2018			1993–2008	2005–2008
Vaquita protection area	Option 1	Option 2	Option 3		
Median R_*	0.73	0.89	1.36	0.30	0.75
P(success)	0.08	0.35	0.995	<0.0001	<0.0001

0.49, $f_{N_2} = 0.79$, and $f_P = 0.52$ (Table 2). Prior distributions were modified by the data to varying degrees (Table 2, Appendix S1).

Under Vaquita Protection Area Option 1, which represents the current (2010) level of protection and fishing effort, the probability of success (*i.e.*, that the vaquita population will increase by 2018) was 0.08 (Table 3). The median population size in 2018 was predicted to be 0.73 of its size in 2008 (Table 3)—that is, a 27% decline. The probabilities of success were 0.35 for Option 2 and 0.995 for Option 3, with median population changes between 2008 and 2018 of −11% and +36%, respectively (Table 3). There was considerable uncertainty about the value of R_{PACE} under each of the proposed options (Fig. 2). For example, under Option 3, which assumed vaquita bycatch will end in 2010, the R_{PACE} 95% PI included values from 1.06 to 2.01—that is, a 6% to 101% increase in population size between 2008 and 2018. Uncertainty was largest for Option 2.

The probabilities of past success for $R_{reserve}$ and R_{refuge} were both <0.0001 (Table 3). Thus it was nearly certain that the vaquita population decreased between the years the Biosphere Reserve and the Refuge Area were established, 1993 and 2005, respectively, and 2008. Between 1993 and 2008 the population was estimated to have declined by 70%, and between 2005 and 2008 by 25% (median *R* of 0.30 and 0.75, respectively, Table 3).

If the implementation of PACE Vaquita was delayed, the probability of success decreased. The probability of success was 0.995 if vaquita bycatch ended in 2010, and decreased to 0.97, 0.89, 0.76, 0.58, 0.41, 0.28, and 0.18 for each year after 2010 before bycatch ended (Table 4). The wide posterior distributions of R_{PACE} reflected the large amount of uncertainty (Fig. 3).

Partial implementation of the plan also reduced the probability of success. If vaquita bycatch was not completely eliminated (0% of the preplan 2007 level), but was reduced to 10%, 20%, 30%, 40%, 50%, 60%, or 70% of the 2007 level, the probability of success decreased from 0.995 to 0.95, 0.83, 0.62, 0.40, 0.25, 0.14, and 0.08, respectively (Table 4). For each scenario of degree of implementation, there was considerable uncertainty about future population size (Fig. 4).

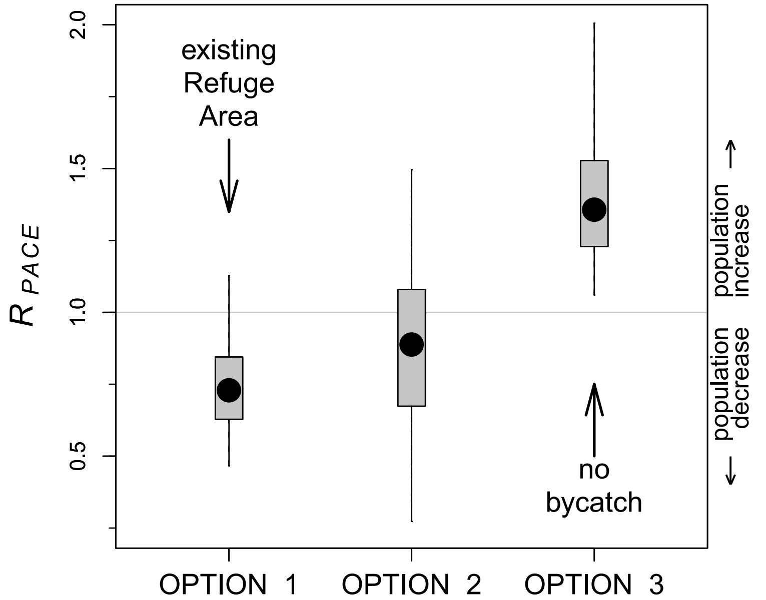

Figure 2. Scenarios of three protected area options proposed in the PACE Vaquita conservation plan. Boxplots show the posterior probability distributions of R_{PACE}, the ratio of vaquita population size in 2018 to population size in 2008, under the three options. For each distribution, the circle is the median, the gray box is the central 50% and the vertical line the central 95% probability interval.

Before the initiation of PACE Vaquita in 2008, the number of vaquitas taken as bycatch was declining (Fig. 5), but the percentage of the population taken as bycatch was increasing (Fig. 6). The median estimates of vaquita bycatch in 2007, before the reduction in fishing effort and enforcement of the Refuge Area, were 35 vaquitas and 15% of population size. The government buyout (or temporary rent-out) of gill net boats in 2008 and 2009,[6] together with enforcement of the Refuge Area, greatly reduced the number and fraction of vaquitas taken as bycatch (Fig. 5, 6). Under the assumption that fishing effort would remain at the 2009 level, the median vaquita bycatch rate was 6.7% (95% PI 3.0–11.9) under Option 1 and 4.2% (95% PI 0.3–17.7) under Option 2. Under Option 3 bycatch was zero by assumption.

The size of the vaquita population was estimated to have declined from 664 in 1993 to 209 in 2009 (Fig. 7A, median values). In 2008 abundance was estimated to be 214 animals (95% PI 135–326). If Option 3 were to be implemented in 2010, the population was projected to increase to 302 (95% PI 174–536) animals by 2018 (Fig. 7B). Under Option 2, the population was projected to decrease to 198 (95% PI 54–417) by 2018, while under Option 1, the population was projected to decrease to 163 (95% PI 77–319) by 2018.

[6]Personal communication from L. Fueyo, Comisionado, Comisión Nacional De Áreas Naturales Protegidas (CONANP), Camino Al Ajusco No. 200, Col. Jardines En La Montana, Deleg. Tlalpan. C. P. 14210, Mexico, 29 July 2010.

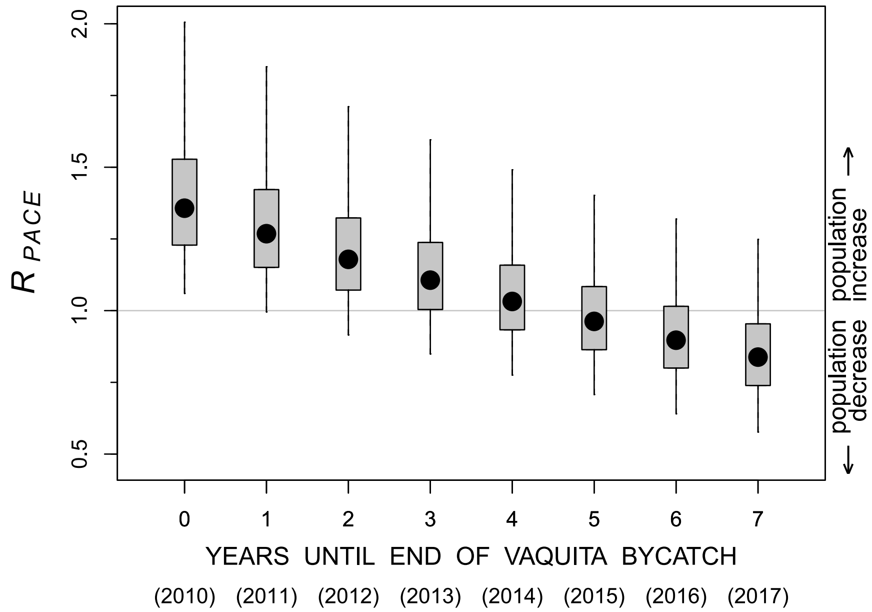

Figure 3. Scenarios of delayed implementation of the PACE Vaquita conservation plan. Boxplots show the posterior probability distributions of R_{PACE} as a function of the number of years until vaquita bycatch is eliminated. The calendar year is shown in parentheses. Symbols are the same as in Figure 2.

Discussion

Probable Success of the PACE Vaquita Conservation Plan

In 2007, prior to the conservation plan, the estimated annual bycatch of vaquitas in gill nets was high, about 15% of population size (Fig. 6), and the population was declining (Fig. 7A). Under the initial phases of PACE Vaquita in 2008 and 2009, the number of gill net boats was reduced by approximately 30%. This reduction in fishing effort, together with enforcement of the ban on gill net fishing in the Refuge Area, led to a sharp decrease in estimated vaquita bycatch in 2008 and 2009 (Fig. 5).

Option 1 would continue the ban on gill net fishing in the Refuge Area. If fishing continues at the 2009 level, bycatch will be about 7% of vaquita population size (Fig. 6). Because this is higher than most of the probable values of the population growth rate *r* (Table 2), there was only a small probability (0.08, Table 3, Fig. 2) that the population would increase by 2018 under Option 1. The median outcome was that the population would decline by 27% (Fig. 7B). The Refuge Area, which covers about one-quarter of the vaquita's range but contains about one-half of the population, was not designed to allow the population to recover; rather, it was proposed by the CIRVA recovery team as a measure to buy time to implement an economic compensation scheme and to develop alternative fishing gear.

Option 2 had a greater probability of success than Option 1 (Fig. 2). Option 2 included 77% of the area in the vaquita range, and an estimated 79% (with large uncertainty, Table 2) of the population. (The spatial distribution of sightings in

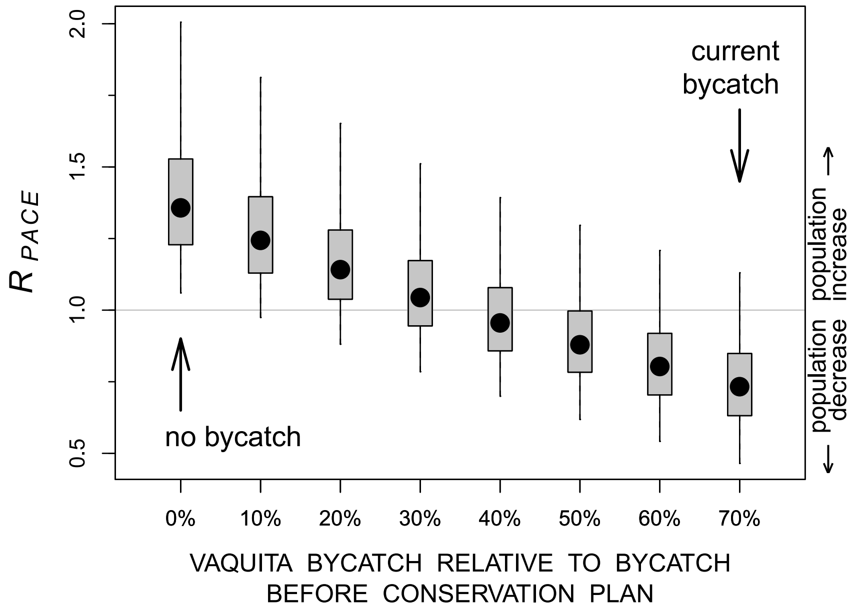

Figure 4. Scenarios of partial implementation of the PACE Vaquita conservation plan. Boxplots show the posterior probability distributions of R_{PACE} as a function of the amount of vaquita bycatch relative to 2007, prior to the PACE Vaquita conservation plan. Current (2010) fishing effort is 70% of the preplan level. Symbols are the same as in Figure 2.

Figure 1 do not give an accurate picture of vaquita density, because the spatial distribution of transect effort is not shown. There was little effort outside the Option 2 area, so the single vaquita detection received a lot of weight.) However, even with the optimistic assumption that all fishing effort currently in the Option 2 area would retire or move out of the vaquita's range, the probability of success was only 0.35 (Table 3). In other words, it was approximately twice (0.65/0.35) as likely that the population would decrease than that it would increase under Option 2. If any of the current fishing effort in this area did continue outside, the probability of success would be lower. Starting in 2010, bycatch would be about nine vaquitas per year (Fig. 5) and 4% of population size (Fig. 6). R_{PACE} was estimated with less precision (a wider posterior distribution) for Option 2 than for Options 1 or 3 (Fig. 2), because Option 2 required estimation of all nine parameters in Table 2, while Options 1 and 3 only required estimation of the first seven.

Option 3, with zero bycatch starting in 2010, gave the most complete protection to the vaquita and had >0.99 probability of success by 2018 (Table 3). The high probability of success for Option 3 was simply a consequence of the assumptions that bycatch was the only factor preventing population growth (Eq. 1) and that the population growth rate was positive (Table 2). Lack of success ($R_{PACE} < 1$) was only possible with a high bycatch rate in 2008 and 2009 together with a low population growth rate, a combination with very low probability.

Not surprisingly, delayed (Fig. 3) or partial (Fig. 4) implementation of the conservation plan lowered the probability of success. Failure to eliminate vaquita bycatch

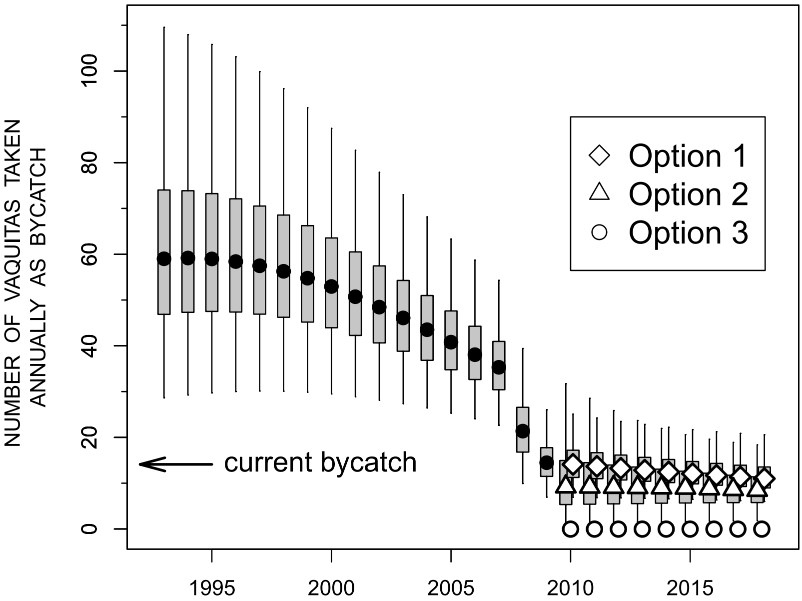

Figure 5. Estimated annual vaquita bycatch B_t. Bycatch beginning in 2010 is shown separately for the three protected area options proposed in PACE Vaquita. Symbols are the same as in Figure 2.

completely under PACE Vaquita would occur if Option 1 or Option 2 were chosen, if the buyout were not complete, if enforcement were not complete, if there were fishing by unregistered boats, if alternative fishing methods did not completely eliminate bycatch, or if there were vaquita mortality due to factors not considered in the model. Because all of these factors are possible, even if Option 3 is selected it is likely that some vaquita bycatch will continue. Bycatch will have to be reduced to at least 30% of the preplan level (*i.e.*, a reduction of 70%) in order to have >50% chance of success (Fig. 4, Table 4).

Population Model

The population model provided a framework to bring the different kinds of available data—abundance estimates, bycatch estimates, acoustic data, and fishing effort—together to estimate the success of three different protected area options under PACE Vaquita. Combining multiple kinds of data allows improved estimates of abundance, status, and trends (Goodman 2004). For example, Gerrodette *et al.* (in press) estimated a 2008 population size of 245 (95% CI 68–884), based on line-transect data (Table 1). When this estimate was combined with other data in the model, the median 2008 abundance estimate was lower and more precise (214, 95% PI 135–326) (Fig. 7A). Although standard confidence intervals and Bayesian posterior probability intervals (also called credibility intervals) mean different things, it is clear that the model-based estimate had higher precision because it was supported by more data.

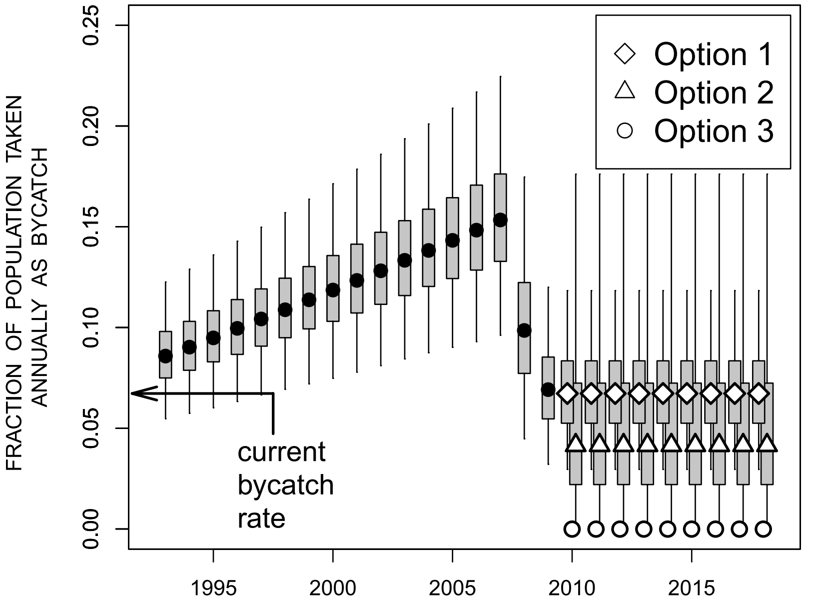

Figure 6. Estimated fraction of the vaquita population taken annually as bycatch B_t/N_t. Bycatch fractions beginning in 2010 are shown separately for the three protected area options proposed in PACE Vaquita. Symbols are the same as in Figure 2.

Similarly, it has been clear for years that available vaquita bycatch data were too high to be compatible with available abundance data. D'Agrosa *et al.* (2000) estimated a bycatch of 39 vaquitas in 1993 from El Golfo de Santa Clara. These authors and subsequent analyses, including this one, doubled the estimate to 78 to account for fishing from San Felipe. When combined with other data in the population model, the median estimate of 1993 bycatch was 59 vaquitas (95% PI 29–110) (Fig. 5). Thus a 1993 bycatch of 78 vaquitas was not improbable, but a lower value of 59 was more probable, given other data. Also, the bycatch rate may have been higher in 1993 than other years (process error) due to factors not considered in the model.

For estimating the success of PACE Vaquita, Bayesian methods allowed the uncertainties about vaquita population size, bycatch, and spatial distribution to be carried through the analysis to evaluate the consequences of alternative management actions (Punt and Hilborn 1997). Including measurement or observation error is important for accurate estimation of demographic processes (Calder *et al.* 2003, Hovestadt and Nowicki 2008). The model did not, however, include process error (temporal variation in the parameters) due to the limited amount of data. For example, available data were not sufficient to contribute to the estimation of a single population growth rate *r* (Table 2, Appendix S1), much less a different rate in each year or a distribution of rates in a hierarchical model. Addition of a moderate amount of process error as informative priors in sensitivity trials increased the spread of the posterior distributions, but did not affect the basic conclusion that Options 1 and 2 were unlikely to provide sufficient protection to allow the vaquita population to recover with high probability.

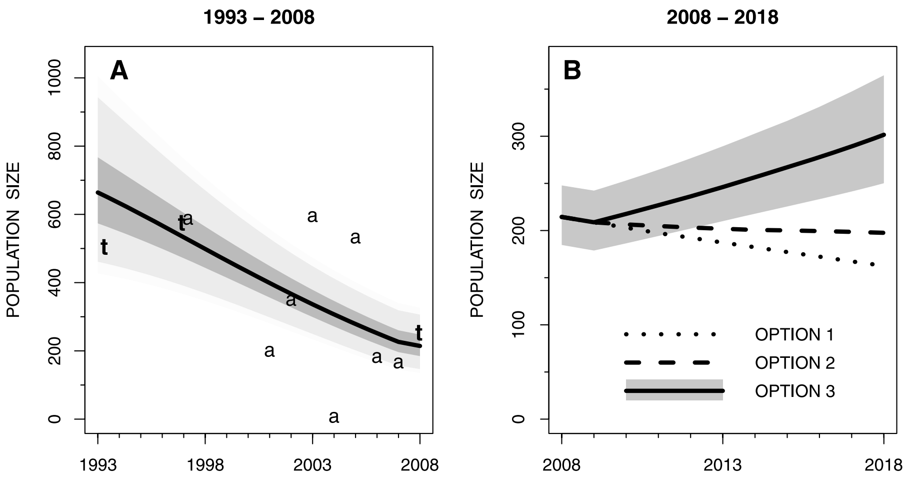

Figure 7. Estimated trajectories of vaquita abundance N_t. (A) Prior to the PACE Vaquita conservation plan, 1993–2008. The line connects the medians of the posterior distributions and the three shades of gray indicate the central 50%, 90%, and 95% of probability density. The letters "a" and "t" indicate acoustic and transect data used to fit the model, using the median value of a to plot the acoustic data and the median value of f_c to plot the partial 1993 abundance estimate on the scale of total population size. (B) After initiation of the conservation plan, from 2008 to 2018, under three different protected area options beginning in 2010. The lines connect the medians of the posterior distributions. The gray area indicates the central 50% of probability density under Option 3.

The data were informative for all parameters except r and b (Table 2, Appendix S1). Although the data did not change our knowledge of r and b, inclusion of these parameters in the model was important because it brought uncertainty about population growth rate and fishing effort into the analysis. The estimates of success for the various scenarios of the conservation plan (Table 3, 4) included all reasonable values of these parameters, weighted by their prior probabilities. R_{PACE} for each option was correlated positively with r, negatively with N_{1992} and, for Options 1 and 2, positively with the fraction of the population in the protected area (Appendix S2–4). Similarly, probability of success was a positive function of r and the fraction of the population and fishing effort in the protected area for Options 1 and 2 (Appendix S5). For Option 3, probability of success was not strongly related to any of the parameters except values of r less than about $0.2 \times 0.14 = 0.028$ (Appendix S5).

Because f_{N_1} and f_{N_2} were not time-dependent, the model assumed that the relative spatial distribution of vaquitas did not change between 1993 and 2010, and would not change in the future. More realistically with density-dependent habitat selection (MacCall 1990), f_{N_1} and f_{N_2} would be expected to decrease as the population recovers. If this happens, because the probability of success was an increasing function of the fraction of the population within the VPA area (Appendix S5), our estimates of success for Options 1 and 2 would be too high. Based on a limited amount of acoustic sampling outside the core area, Jaramillo-Legorreta (2008) speculated that the range of the vaquita may have shrunk as the population declined in the last decade. The model also assumed implicitly that the vaquita distribution does not change seasonally. The estimates of f_{N_1} and f_{N2} were based on data collected in late

Table 4. Probability of success for scenarios of delayed or partial implementation of the PACE Vaquita conservation plan. R_{PACE} is the ratio of population size in 2018 and 2008 (see Methods), and the median of the posterior distribution is shown for each scenario. Values of P(success) show the probability that the vaquita population would increase between 2008 and 2018 for each scenario. Results with 0 years until end of bycatch or 0% gillnet fishing effort were the same as protected area Option 3 in Table 3 because all assumed vaquita bycatch would end in 2010.

Scenario	Delayed implementation							
Units	Years until end of vaquita bycatch							
Amount	0	1	2	3	4	5	6	7
Median R_{PACE}	1.36	1.27	1.18	1.11	1.03	0.96	0.89	0.84
P(success)	0.995	0.97	0.89	0.76	0.58	0.41	0.28	0.18
Scenario	Partial implementation							
Units	Gillnet fishing effort in vaquita range relative to 2007							
Amount	0%	10%	20%	30%	40%	50%	60%	70%
Median R_{PACE}	1.36	1.24	1.14	1.05	0.96	0.88	0.80	0.73
P(success)	0.995	0.95	0.83	0.62	0.40	0.25	0.14	0.08

summer and fall. If vaquitas spend more time in shallow water at other times of the year, our estimates of the probability of success would again be too high.

The posterior mode of the bycatch rate q was similar to the prior, but the data increased the precision of q (Table 2, Appendix S1). The prior distribution was based on the data of Fleischer *et al*. (1996), who concluded without analysis that, since only four vaquitas were killed in 682 sets, bycatch did not threaten the vaquita population. In fact their observed bycatch rate, which was supported by the current analysis, was high enough to cause the vaquita population to decline (Fig. 7A). The model also assumed that each encounter of a vaquita with a net was an independent event. Data from line-transect surveys showed, however, that vaquitas have a clumped distribution (Jaramillo-Legorreta *et al.* 1999, Gerrodette *et al.*, in press), so it is possible that a large number of vaquitas could be caught in a limited area in a short period of time.

We assumed that Option 3 included the entire range of the vaquita. Although the Option 3 area included all confirmed sightings, acoustic detections and bycatch records in the last 30 yr, there is some chance that vaquitas occur outside. Gerrodette *et al*. (1995) reported two vaquita sightings outside the Option 3 area, although neither sighting was considered certain. Norris and McFarland (1958) reported probable vaquita sightings from the northeastern Gulf in the 1950s and earlier, considerably outside the currently known range. If vaquitas do occur outside this area and are exposed to gill net mortality, our estimates of the probability of success would be too high.

Although there were uncertainties about the size of the vaquita population in any single year, the trend of the population was clear (Fig. 7A). Jaramillo-Legorreta *et al*. (2007) made a nonstatistical projection of 150 vaquitas in 2007 from previous estimated and expected trends. Jaramillo-Legorreta (2008) used a Bayesian population model to estimate median population sizes of 5,015 vaquitas in 1920 and 93 in 2007. According to the results of this paper, the median 2007 abundance was 226 vaquitas (95% PI 145–340). The higher and more precise estimate of this paper compared to Jaramillo-Legorreta (2008) was due to inclusion of the 1993 and 2008 abundance data as well as a different model structure.

Determining Whether the Conservation Plan Is Working

From the individual fisherman's point of view, it is difficult to understand how bycatch of vaquitas can be important because it is so rarely observed. Indeed, many fishermen in the area claim they have never seen a vaquita, dead or alive. The current (2010) annual bycatch was estimated to be about 14 vaquitas (Fig. 5). Given this level of bycatch, only about 2% (14/589) of boats will catch a vaquita (less if one boat takes more than one vaquita), which means that 98% of boats will not observe any bycatch of vaquita during the entire year. If each boat makes 100 trips a year, the probability of vaquita bycatch on a single trip is 0.0002. Understandably, it is difficult to communicate that such rare events can have significant effects, and thus to convince fishermen that restrictions on fishing are needed.

The rarity of vaquita bycatch also means that it will be difficult to demonstrate differences in bycatch rate between existing gill nets and alternative gear currently being tested, and thus to know whether alternative gear is effective at reducing bycatch. An observer program of sufficient size to detect a reasonable number of vaquita mortalities would be prohibitively expensive (Jaramillo-Legorreta *et al.* 2007). The most direct way to determine if the conservation plan is succeeding is to measure an increase in vaquita population size. Individual estimates of absolute abundance have large uncertainty, however, so it would be difficult, as well as expensive, to determine recovery based solely on periodic surveys (Taylor and Gerrodette 1993). Acoustic monitoring of relative abundance (Rojas-Bracho *et al.* 2010) offers the most economical means to monitor future changes in vaquita distribution and abundance.

The policy of the Mexican government's Ministry of the Environment, as expressed in PACE Vaquita, is to eliminate vaquita bycatch. This is the appropriate policy to avoid further decline and possible extinction. However, whether the current voluntary buyout scheme can achieve elimination of bycatch seems doubtful. Fishing is an important component of the local economy (Aragón-Noriega *et al*. 2010, Rojas-Bracho and Fueyo 2010), and only about one-third of the fishermen have accepted the buyout terms so far. There is a hard-core group of fishermen who want to continue to fish no matter what economic alternatives are offered. The remaining fishermen may benefit from less competition for the resources (shrimp and finfish), making it harder to buy them out on a voluntary basis. If gill net fishing continues in the vaquita's range, however, we cannot be certain that the vaquita population will recover, based on the results presented here. In order to have a high probability that vaquita abundance will increase, bycatch will have to be reduced to a small fraction of the preplan level (Fig. 4), and Options 1 and 2 do not achieve this (Fig. 2). The goal of eliminating vaquita bycatch could be achieved by banning gill nets within the entire range of the species (Option 3), total buyout of gill nets, or conversion to alternative gear that has no vaquita bycatch.

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Appendix S1. Prior and posterior distributions and likelihood functions for the nine basic parameters of the vaquita model, and five derived parameters: R_{PACE}

Options 1–3, $R_{reserve}$ and R_{refuge}. The latter five were plotted over the same range for comparison. All curves were scaled to enclose the same area within each plot, relative to the maximum of the posterior distribution.

Appendix S2. Joint posterior probability contour plots of each parameter of the vaquita model with the ratio R_{PACE} for Option 1 of the PACE Vaquita conservation plan.

Appendix S3. Joint posterior probability contour plots of each parameter of the vaquita model with the ratio R_{PACE} for Option 2 of the PACE Vaquita conservation plan.

Appendix S4. Joint posterior probability contour plots of each parameter of the vaquita model with the ratio R_{PACE} for Option 3 of the PACE Vaquita conservation plan.

Appendix S5. Logistic regressions of the probability of success for each of the nine parameters of the population model for each of the three options of the PACE Vaquita conservation plan. The value of each parameter is plotted on a relative scale from 0 to 1 as a fraction of its range shown in Figure A1. Some lines are so close to others that they are hidden.