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LETTER

Extinction is Imminent for Mexico's Endemic Porpoise Unless Fishery Bycatch is Eliminated

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Abstract

The number of Mexico's endemic porpoise, the vaquita (*Phocoena sinus*), is collapsing primarily due to bycatch in illegal gillnets set for totoaba (*Totoaba macdonaldi*), an endangered fish whose swim bladders are exported to China. Previous research estimated that vaquitas declined from about 567 to 245 individuals between 1997 and 2008. Acoustic monitoring between 2011 and 2015 showed a decline of 34%/year. Here, we combine visual line transect and passive acoustic data collected simultaneously in a robust spatial analysis to estimate that only 59 (95% Bayesian Credible Interval [CRI] 22–145) vaquita remained as of autumn 2015, a decrease since 1997 of 92% (95% CRI 80–97%). Risk analysis suggests that if the current, temporary gillnet ban is maintained and effectively enforced, vaquitas could recover to 2008 population levels by 2050. Otherwise, the species is likely to be extinct within a decade.

Introduction

The vaquita porpoise (*Phocoena sinus*) occupies a tiny geographic range in the northern Gulf of California, Mexico (Brownell 1986; Gerrodette *et al.* 1995), an area of intensive gillnet fishing (Rodríguez-Quiroz *et al.* 2010). Vaquita bycatch in gillnets in the early 1990s was estimated to be unsustainable (D'Agrosa *et al.* 2000). Between 1997 and 2008, vaquita numbers declined at an average annual rate of 7.6%, from an estimated 567 (95% confidence interval (CI), 177–1,073; Jaramillo-Legorreta *et al.* 1999) to 245 animals (95% CI, 68–884; Gerrodette *et al.* 2011).

Between 2011 and 2015, a passive acoustic monitoring program determined that vaquita abundance was declining by 34%/year (95% CRI, −48% to −21%; Jaramillo-Legorreta *et al.* 2016). Much of this decline resulted from the resurgence of illegal gillnetting to supply swim bladders of totoaba (*Totoaba macdonaldi*) to lucrative Chinese markets (Valenzuela-Quiñonez *et al.* 2015; Anonymous 2016a, 2016b). Totoabas are large endangered endemic fish about the same size as vaquitas. Swim bladders from wild fish are large making them both more valuable and diagnosable as non-aquaculture products. Preliminary results from the acoustic monitoring prompted the Government of Mexico to enact an emergency 2-year ban of gillnets throughout the vaquita's range starting May 2015. Vaquita recovery will take much longer than 2 years and extension of the ban will be controversial. Information on the current population size will provide added evidence to justify extending the ban.

The difficulty of obtaining precise abundance estimates for rare and cryptic species plagues conservation biology (Taylor & Gerrodette 1993). Nevertheless, our study objective was to obtain such an estimate of the number of vaquitas remaining at the beginning of the 2-year gillnet ban. We achieved this objective, despite the catastrophic decline, by drawing on the strengths of an international, multidisciplinary team, by implementing a study design (using the same ship and methodology) and analyses that used past data to inform estimates of current abundance, and by combining multiple data types (acoustic and visual surveys) through a spatial analysis framework. We projected this population estimate forward under the best and worst scenarios: continued ban with perfect enforcement and maximum population growth; and a post-ban return to the 2011–2015 rate of decline.

Materials and methods

Details for abundance estimation appear in Supporting Information Appendix 1 (SI-A1). SI is provided for risk analyses (SI-A2), consideration of potential biases (SI-A3), visual data (SI-A4), and acoustic data (SI-A5).

Study design

Our visual survey (28 September–4 December 2015) covered the entire range of vaquitas (Figure 1) in waters between 20- and 50-m deep. We used the same 52-m ship and visual line-transect survey methods used in 1997 and 2008 (Jaramillo-Legorreta *et al.* 1999; Gerrodette *et al.* 2011b). Two strata were defined (visual and shallow), with higher visual survey effort in a core sub-stratum (Figure 1). The ship could not survey in depths <20 m (Figure 1, shallow stratum); vaquitas were detected there using an array of C-POD passive acoustic detectors (Tregenza *et al.* 2016). Abundance cannot be estimated directly using acoustic detections because we lack information on vaquita acoustic behavior and sound propagation. Therefore, an array of acoustic detectors was also deployed in part of the core sub-stratum (Figure 1, calibration area) and the relationship between visual and acoustic information in this area was used to estimate abundance from acoustic data in the shallow stratum. We assumed vaquita clicks have the same probability of detection in the shallow stratum and calibration area and vocal behavior was the same (bias exploration in SI-A3).

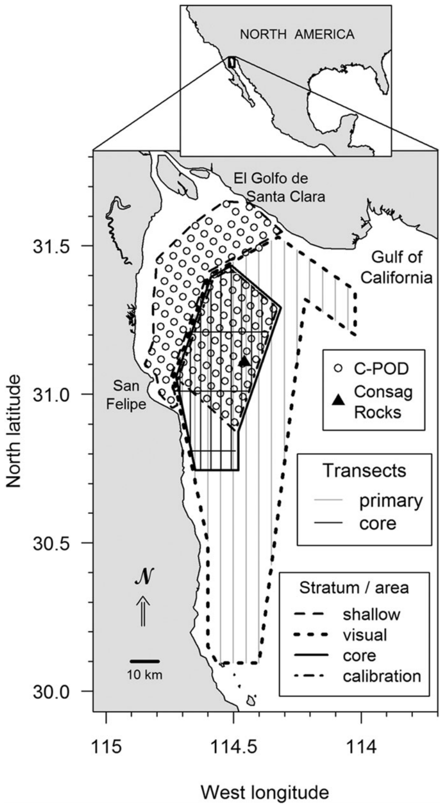

Figure 1 Research design for the 2015 vaquita abundance study. Vaquitas were detected acoustically with recording devices (C-PODs) in the shallow stratum, and visually with a line-transect survey in the deeper visual stratum. The calibration area had both visual and acoustic sampling. The core sub-stratum was the central part of the vaquita range within which abundance was compared in 1997, 2008, and 2015 for trend estimation. Positions shown are pre-cruise planned sampling locations. Consag Rocks are a prominent local landmark.

Core sub-stratum abundance and trend: 1997, 2008, 2015

We estimated vaquita abundance in the core sub-stratum (Figure 1) for 1997, 2008, and 2015 using visual line-transect data collected during sea conditions of Beaufort scale ≤2 and swell height ≤0.6 m (Table 1 and Figure 2). We used a model-based distance-sampling approach (*sensu* Buckland et al. 2001; Borchers *et al.* 2002, 2004), extended from conventional methods in two primary ways. First, following Barlow (2015), we estimated

Table 1 Summary of visual line-transect effort and vaquita sightings included in the analysis, and population size estimates (*N*) with coefficients of variation (CV, posterior SD/mean) and 95% Bayesian credible interval (CRI). *N* is given by the median of the posterior distribution. Effort is the length of transect conducted in Beaufort ≤2 and swell height ≤0.6 m. Number of groups sighted is those seen on effort by observers on the flying bridge within 3.5 km (perpendicular distance) of the vessel and in these effort conditions

	Area (km^2)	Effort (km)	No. groups sighted	Mean group size (SE)	*N* (CV)	95% CRI
Visual core sub-tratum						
1997	1773.42	304.5	84	1.90 (0.15)	557 (0.22)	366–856
2008	1773.42	756.0	90	1.86 (0.14)	166 (0.21)	111–247
2015	1773.42	762.8	14	1.75 (0.35)	47 (0.50)	18–115
All survey strata, 2015						
Visual, inside core sub-stratum	1773.42	762.8	14	1.75	47 (0.50)	18–115
Visual, outside core sub-stratum	3562.96	543.1	0	–	0 (–)	–
Acoustic shallow stratum	1370.58	NA	NA	NA	12 (0.50)	5—30
Total	6706.96	1305.9	14	1.75	59 (0.50)	22—145

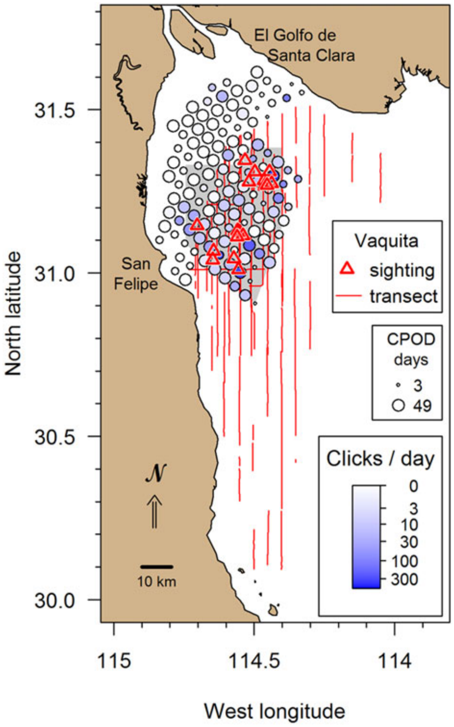

Figure 2 Visual line-transect survey effort (thin red lines) and vaquita sightings (triangles) in 2015 in conditions of Beaufort ≤2 and swell height ≤ 0.6 m. C-PODs are the acoustic recording devices. C-POD circle size indicates the number of days of acoustic effort used in the analysis at each location, between 3 (minimum) and 49 (maximum) days. Shading of the circles indicates the mean observed number of vaquita clicks per day. Gaps in the C-POD grid are due to loss of C-PODs. The gray polygon in the background is the Vaquita Refuge Area.

the proportion of vaquita on the transect line that went undetected (parameter $g(0)$) as a function of sighting conditions; conventionally a single estimate is applied for a survey. Changes in $g(0)$ are relative to its value in ideal conditions (zero Beaufort and swell), which we estimated using a mechanistic model of animal and observer behavior, fitted to radial detection distances (Barlow 1999). Second, using a Bayesian approach, we modeled animal density at the level of small transect segments, accounting for spatial correlation in detections via an intrinsic autoregressive (IAR) process (Besag & Koopersberg 1995) and modeling potential geographic range contraction through time as a state-space process. Model fitting was performed using a Markov Chain Monte Carlo (MCMC) algorithm.

To implement the spatial model, the core sub-stratum was overlaid with a spatial grid of 50 points (denoted j) with 6-km spacing. Transect effort was cut into ≈1-km segments (denoted i). Each i was assigned to the nearest j. We modeled the number of groups sighted on each segment as a negative binomial random variable, $n_i \sim NB(\mu_i, \alpha)$, where μ_i is the expected count and α is an overdispersion parameter. The expectations were

$$\mu_i = \frac{d_{t[i]}}{s_{t[i]}} \cdot \exp\left(z_{j[i]}\right) \cdot I_{j[i],t[i]} \cdot 2L_i\omega_i g(0)_i, \tag{1}$$

where d_t is the mean animal-density parameter for the core sub-stratum in year t ([i] indicates the value associated with segment i); s_t is the mean number of individuals per sighted group; z_j is a spatially correlated random effect (same for all t), estimated from the IAR model component; $I_{j,t}$ is a latitude-dependent indicator for whether location j remains within the vaquita's potentially contracting geographic range at t (state-space model component); L_i is the segment length (km); ω_i is the covariate-dependent effective strip half-width (km) (distance-sampling model component); and $g(0)_i$ is the probability of detecting a vaquita on the transect line.

The estimate for D_{jt}, vaquita density at j, t, equals $d_t \exp(z_j) I_{j,t}$. Averaging these across the j gives the annual mean density D_t, which, multiplied by the core sub-stratum size (Table 1), gives the core-sub-stratum abundance N_t. The average annual rate of change from time t_1 to t_2 is $\lambda = (\frac{N_{t_2}}{N_{t_1}})^{1/(t_2-t_1)}$.

Vaquita abundance: 2015

Abundance for 2015 was calculated as the sum of abundances from the visual and shallow strata (Figure 1), but because no sightings were made outside the core sub-stratum (described in the previous section), we express: $N_{\text{total}} = N_{\text{core}} + N_{\text{shallow}}$. The total for the shallow stratum, N_{shallow}, was estimated as the ratio of acoustic activity in the shallow stratum to the calibration area applied to the abundance estimate in the core sub-stratum, $\hat{N}_{\text{shallow}} = c \times \hat{N}_{\text{calibration}}$, where $\hat{N}_{\text{calibration}}$ is the mean of the D_{jt} for the j locations within the calibration area, multiplied by its size (1354.57 km^2). To obtain c, we used model-based geostatistics (Diggle *et al.* 1998). Let the number of detection positive seconds (DPS) per day, from the acoustic grid data, be denoted $Y(\mathbf{s},a)$ for spatial location $\mathbf{s}$ (containing spatial coordinates) on day a. The $Y(\mathbf{s},a)$ were assumed to be distributed Poisson $(\lambda(\boldsymbol{s}, a))$, where

$$\log(\lambda(s, a)) = \mu + \log(r_{\text{a}}) + V(s, a) + \varepsilon(s, a),$$

where μ is the overall mean, r_a is effort on day a (forming an offset), $V(\mathbf{s},a)$ is a spatially autocorrelated random effect for day a, and $\varepsilon(\mathbf{s},a)$ is independent random error. We used MCMC to obtain 500 posterior samples of all parameters, including $V(\mathbf{s},a)$, for all observed $\mathbf{s}$ and a. We used kriging (e.g., Cressie, 1993, p. 105) on this posterior sample to obtain 500 predictions of $\log(\lambda(\mathbf{s},a))$ (for constant effort r_a) over 6096 evenly spaced points clipped to the shallow stratum and calibration areas for each day. After exponentiating, the daily ratio of predicted values in the shallow stratum to the calibration area was denoted c_a, and these c_a averaged across days when both visual and acoustic survey methods were fully employed to estimate c for each MCMC sample. The 500 MCMC iterations provided a posterior sample for c, allowing inferences such as mean and standard error.

Extinction risk analysis

We projected future population size from 2015 under two scenarios assuming: (1) no further human-caused mortality occurs and the population grows at its intrinsic annual rate of 3.8% (Gerrodette & Rojas-Bracho 2011a); (2) no population change from 2015 to 2017 (during current gillnet ban) followed by a 34% annual decline (95% Bayesian credible interval [CRI]: 21% to 48%; Jaramillo-Legoretta *et al.* 2016). SI-A2 gives additional scenarios representing a continuing ban but with imperfect enforcement. We also calculated the number of human-caused deaths, given current population size, that would result in no population growth.

We based Monte Carlo projections of abundance (5000 simulations per scenario) on simple deterministic models. Forecasts reflected uncertainty only in the estimates of 2015 abundance and the rate of decline (scenario 2). We did not account for depensation. We evaluated the annual probability of vaquita abundance declining to below a quasi-extinction (QE) level of 10 individuals and the expected time for this to occur (when $\text{Prob}(N < 10) = 0.5$). SI-A2 gives additional scenarios and thresholds.

Results

Ship transects achieved reasonably uniform coverage of strata in 2015 (Figure 2). Fourteen vaquita sightings during 1305.9 km of searching effort satisfied criteria for inclusion in the analysis (see SI-A1), all within the core stratum (Table 1). The selected detection function is described in SI-A1. The probability of sighting a vaquita on the transect line, $g(0)$, in sea conditions of zero Beaufort and swell was estimated to be 0.975 (CV 2.1%; see SI-A1). In higher Beaufort and swell conditions, detection probability was greatly reduced. Group size was similar to past years (1.75; Table 1). The best Bayesian spatial model indicated a reduction in geographic range from 1997 to 2015 (Figure 3A–C).

There were 49 days during the visual survey when the acoustic grid was fully operational. Within the calibration area, sightings and acoustic activity showed similar spatial patterns (Figures 2 and 3D). Vaquitas were also acoustically detected in shallow water areas near El Golfo de Santa Clara and San Felipe. The abundance of vaquitas in the shallow stratum was estimated to be 12 (c [0.28, SE 0.02] multiplied by abundance in the calibration area [44, SE 24] (Table 1)).

The estimated total number of vaquitas was 59 (95% CRI 22–145). The probability that fewer than 50 remain is 36% and that fewer than 100 remain is 87% (Figure 4). Trends are best indicated by changes in numbers within the core sub-stratum, which was covered in all 3 surveys (Table 1). From 1997 to 2015 vaquitas decreased by 92% (95% CRI 80–97%).

If the vaquita population could grow at its maximum intrinsic rate, it would not reach 2008 levels (>250 vaquita) until 2050, or 1997 levels (>600 vaquita) until after 2075. Given current abundance, the population will not grow unless fisheries bycatch is fewer than 2.2 vaquitas (CRI 0.9–5.5) per year. Returning to pre-ban rates of decline, quasi-extinction is expected by 2022 (Figure 5), and full extinction within a decade.

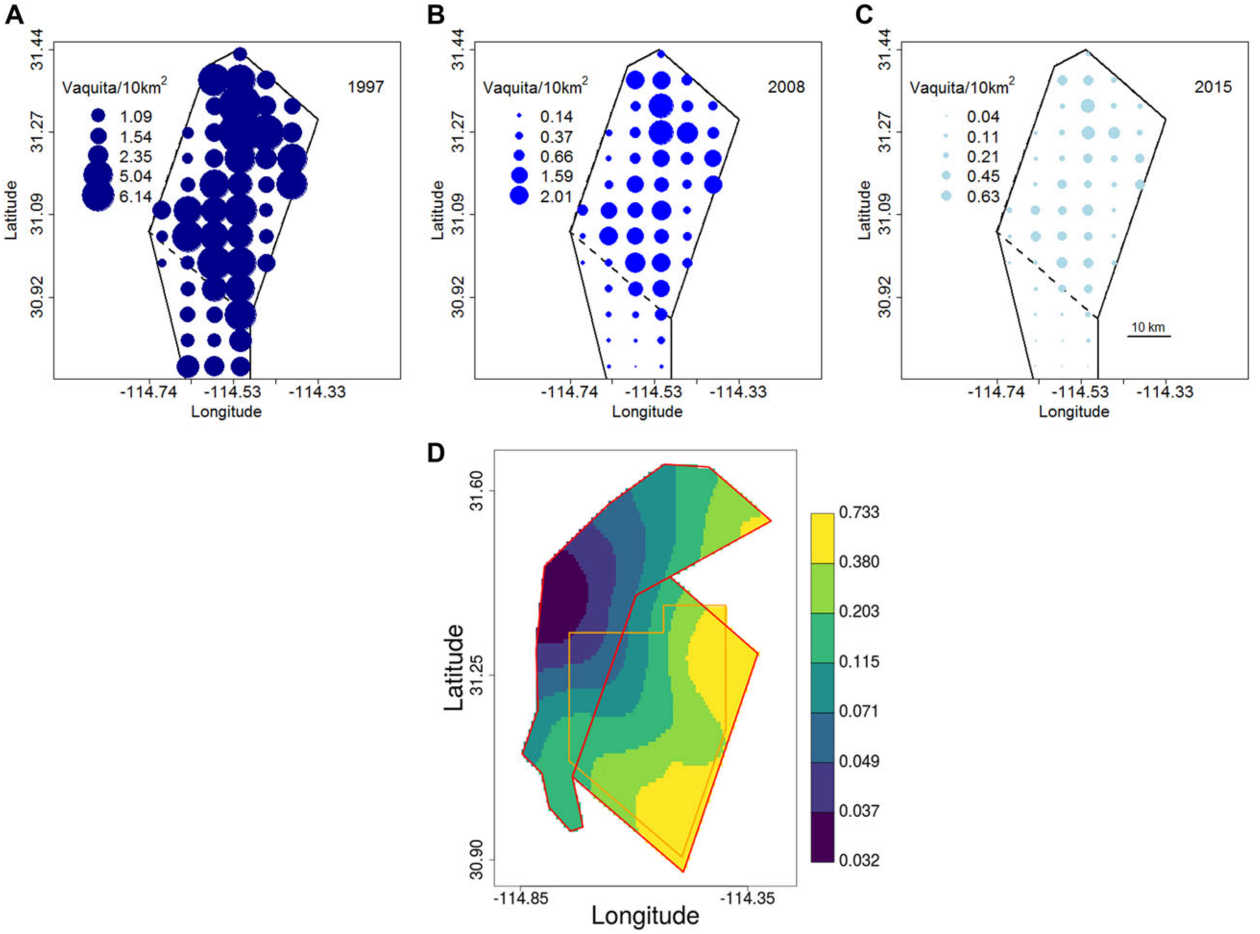

Figure 3 Maps of vaquita density in the core sub-stratum, predicted from analysis of visual line-transect data, for 1997 (A), 2008 (B), and 2015 (C). Acoustic density map for 2015 with average on a log scale (D).

Discussion

Our research confirms with high probability that fewer than 100 vaquitas remain and that the decline since 2008 has been catastrophic. Taylor and Gerrodette (1993) noted that by using traditional analytical methods and null-hypothesis testing, vaquitas could go extinct before a decline was statistically detected. Prior to this study, we identified that the main components of population-size uncertainty stemmed from poor coverage in shallow-water areas, and poor estimates of the probability of detection on the trackline ($g(0)$). In 2015, we obtained moderately precise inferences about the number of vaquitas in shallow-water areas for the first time using passive acoustic detectors combined with Bayesian spatial analytical methods. Although our assumption that vaquita acoustic detection probability is the same in the shallow stratum and the calibration area has only weak support (SI-A3), with only 12 vaquitas estimated to be in shallow waters, the effect of assumption violation on the total number of vaquitas should be negligible. Regarding $g(0)$ estimation, we applied cutting-edge analytical techniques empirically to estimate relative $g(0)$ in different sighting conditions, and used independent information to estimate absolute $g(0)$ under perfect conditions. Using the same visual survey methods and ship as previous years allowed us to share information across years to estimate vaquita spatial distribution and detection probability parameters, and thus to make inferences about current population status despite small sample sizes. As a result, our abundance estimate is more precise than past estimates (1997 CV 51%; 2008 CV 73% vs. 2015 CV 50%).

Until the recent ban, the amount of gillnets set within vaquita habitat had increased despite repeated calls to reduce gillnetting to save vaquitas from extinction (CIRVA 2017). Even with the emergency 2-year gillnet

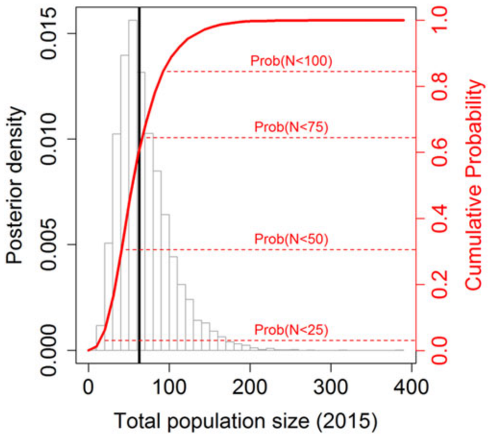

Figure 4 Bayesian posterior distribution for total vaquita abundance in 2015, with vertical dark line indicating posterior median of 59 animals. Cumulative probability distribution (red) indicates the probability that the population size is below any specific level. The probability that $N < 10 = 0.0018$ (not shown).

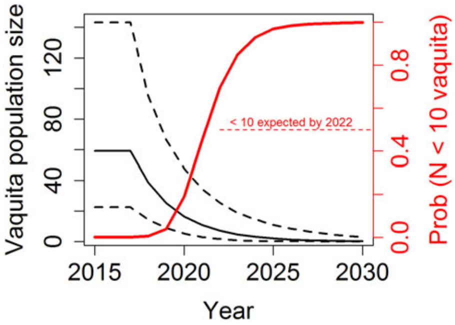

Figure 5 Population viability analysis results for Scenario 3, for which we assume no population change during the gillnet ban (2015–2017) and thereafter a return to the 2011–2015 rate of decline. Solid black trend line is the posterior median; black dashed lines indicate 95% CRIs. Red curve depicts the cumulative probability that there are <10 individuals in each forecast year.

ban, the Mexican Navy in collaboration with the NGO Sea Shepherd removed 42 illegal gillnets and found three vaquitas that died in gillnets between January and May 2016 (CIRVA 2017). These three deaths alone are enough to further the population decline if repeated annually, and it seems unlikely that all dead vaquitas were found. If the gillnet ban is lifted and the population resumes declining at the 2011–2015 rate, the vaquita is expected to remain above a quasi-extinction of 10 individuals for only another 5 years. Although a continued ban with current enforcement levels will postpone the date, extinction is nevertheless inevitable unless gillnets are completely removed from vaquita habitat. The recovery team (CIRVA 2017) noted that although the highest-priority conservation action for vaquitas is creating a gillnet-free habitat, that the continued unchecked illegal totoaba fishery warrants beginning fieldwork to determine the feasibility of *ex situ* conservation (further details in Goldfarb 2017). They also agreed unanimously that capture of all remaining vaquitas is not a viable conservation strategy for vaquitas where the feasibility to capture even a single vaquita is unknown.

Does hope remain? With about 60 vaquitas left, inbreeding warrants concern. Our risk analyses could be overly optimistic by ignoring potential reductions in population growth rate from inbreeding depression, as well as stochasticity or possible Allee effects. Nevertheless, we expect vaquitas should have a reasonable chance of recovery if gillnet deaths were eliminated. Rojas-Bracho and Taylor (1999) concluded that lack of food resulting from changed ecosystem function due to cessation of Colorado River flow was not evident from necropsies of gillnet-killed animals. Necropsies of three vaquitas killed in March 2016 in gillnets revealed that all had full stomachs, supporting that food is still not a limitation (CIRVA 2017). Death in gillnets has been repeatedly determined to be the only threat (Rojas-Bracho & Reeves 2013). Both northern elephant seals (*Mirounga angustirostris*) and Guadalupe fur seals (*Arctocephalus philippii*) were depleted to similar numbers as those for vaquitas and have recovered once humans stopped killing them. If deaths in gillnets were permanently eliminated, there is no reason to doubt that vaquita would recover.

Just 10 years ago, a survey to find the last baijis (*Lipotes vexillifer* a.k.a. Yangtze river dolphin) so they could be moved into semi-natural captivity found none (Turvey *et al.* 2007). As conservation scientists, our response to the unwitnessed baiji extinction was to create and institute the vaquita acoustic monitoring program, which has removed scientific uncertainty about the status of vaquitas. Despite Mexico's increased actions following the scientific results, illegal fishing persists. The lure of thousands of dollars for each totoaba to supply the illegal wildlife trade in mainland China and Hong Kong (Anonymous 2016a, b) apparently outweighs any risk that illegal fishers may fear for being caught within Mexico. Promises to increase penalties and make illegal wildlife trade a felony have not materialized. Illegal wildlife trade remains a critical threat needing international solutions.

Legal gillnet fisheries, however, also pose serious extinction risks for vaquita and other coastal species of megafauna. Bycatch in gillnets remains the greatest threat to marine mammals (Reeves *et al.* 2013) with more than 600,000 killed each year (Read *et al.* 2006). Four species of humpbacked dolphins (*Sousa* sp.) have ranges that completely overlap with such fisheries and all are endangered. Mexico is to be commended for taking strong recent actions, but these must be maintained to save the vaquita. Stopping the cascade of extinctions that will deplete coastal waters of local species will take international support to develop alternative gear and to market the resulting seafood.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Appendices 1–5 are available online. The authors are responsible for the content and functionality of these materials. Queries (other than the absence of the material) should be directed to the corresponding author.

Supporting Information S2
Supporting Information S3
Supporting Information S4
Supporting Information S5

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