

## **Last call: Passive acoustic monitoring shows continued rapid decline of critically endangered vaquita**

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# Last call: Passive acoustic monitoring shows continued rapid decline of critically endangered vaquita

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**Abstract:** The vaquita is a critically endangered species of porpoise. It produces echolocation clicks, making it a good candidate for passive acoustic monitoring. A systematic grid of sensors has been deployed for 3 months annually since 2011; results from 2016 are reported here. Statistical models (to compensate for non-uniform data loss) show an overall decline in the acoustic detection rate between 2015 and 2016 of 49% (95% credible interval 82% decline to 8% increase), and total decline between 2011 and 2016 of over 90%. Assuming the acoustic detection rate is proportional to population size, approximately 30 vaquita (95% credible interval 8–96) remained in November 2016.

[WJL]

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## 1. Introduction

The vaquita (*Phocoena sinus*) is a critically endangered species of porpoise endemic to the northern Gulf of California, Mexico. Vaquitas have been subject to a long history of unsustainable bycatch in gillnets set by small-boat fishers targeting shrimp and finfish (Rojas-Bracho and Reeves, 2013). Recently, there has been a resurgence of an illegal gillnet fishery for an endangered fish, the totoaba (*Totoaba macdonaldi*), fueled by a lucrative illegal trade with China for totoaba swim bladders. This has raised concerns about increased levels of vaquita bycatch. Vaquitas are difficult to monitor using standard visual survey methods (line transects or mark-recapture based on photo-identification) because they are small and visually cryptic, and now are very rare. However, they produce echolocation clicks almost continually, making passive acoustic monitoring of population trends possible. An acoustic monitoring program at a grid of

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locations throughout the core range of the vaquita was started in 2011; analysis of data to 2015 showed an estimated annual decline of 34% [95% credible interval (CRI) 21%–48%] (Jaramillo-Legorreta *et al.*, 2017). Based on preliminary results through 2014, the government of Mexico enacted an emergency ban on gillnets, which began in 2015. However, despite extensive enforcement efforts, there is evidence that illegal fishing and bycatch continue (CIRVA, 2017). Here we report results from the 2016 acoustic monitoring.

## 2. Methods

Hardware deployment, acoustic processing, and trend analysis methods followed those described in detail by Jaramillo-Legorreta *et al.* (2017), and are outlined below.

### 2.1 Acoustic data collection and processing

Forty-six autonomous acoustic loggers were deployed between June and August each year from 2011 to 2016 in a systematic grid within the vaquita refuge, an area of core habitat designated in 2005 [Fig. 1(A)]. Because vaquita now number far fewer than when acoustic monitoring began, 47 additional loggers were added mid July 2016 within the same area to improve precision in future trend monitoring [Fig. 1(B)]. The loggers were C-PODs (Tregenza *et al.*, 2016): autonomous passive acoustic monitoring instruments designed to detect echo-location clicks of toothed whales and store salient features for offline classification. Upon retrieval, proprietary software (C-POD software version 2.044 with KERNO algorithm) was used to detect coherent sequences (“trains”) of approximately regularly spaced clicks and classify them as possible vaquita click trains; all possible vaquita click trains were then manually validated. Data were summarized as the number of vaquita clicks detected per sampling location per day—the “click rate.”

### 2.2 Trend analysis

Only data from the original 46 sampling locations were used for trend analysis. Although this grid of locations was designed to give equal coverage in space and time, in practice sampling was uneven due to shifts in annual deployment dates, equipment failure, and loss. The data set was further truncated to a core sampling period during which at least 50% of the detectors were operating across all 6 years: June 19 to August 19, inclusive (62 days). Nevertheless, the sampling effort was still somewhat uneven, and so trend analysis was based on two Bayesian statistical models developed by Jaramillo-Legorreta *et al.* (2017): a geostatistical model and a non-spatial mixture model. They are described briefly here; full details are given in Jaramillo-Legorreta *et al.* (2017). Both models estimate average click rate per sampling location and year; the mean of these over locations is the average annual click rate. Between-year change in acoustic activity, denoted  $\lambda$ , is estimated as the ratio of the average annual click rates in successive pairs of years.

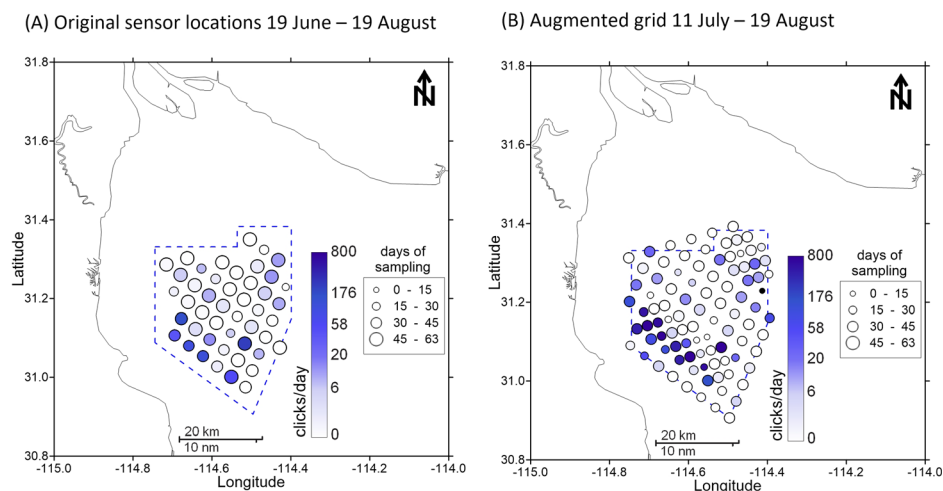


Fig. 1. (Color online) Summary of raw data for 2016. Mean click rate (clicks/day), indicated by shading (note log scale), and days of sampling, indicated by circle size, for (A) the 46 sampling sites grid during the core sampling period (June 19 to August 19), and (B) the augmented 93 sampling sites grid during the part of the core sampling period when additional sensors were deployed (July 11 to August 19).

The geostatistical model compensates for locations with missing data by “borrowing strength” from those around it: the model assumes the average click rate varies smoothly over space, with a separate smooth surface fit to each year of data but with the amount of smoothness (the spatial autocorrelation) the same across years (i.e., autocorrelation parameters estimated from all years’ data). It further accounts for variation in sampling by assuming locations with more sampling days give more precise estimates of the average click rate than those with fewer days.

The post-stratification mixture model probabilistically assigns individual sampling locations to one of three strata. A sampling location is permanently assigned to the same stratum for all years (which is justified based on spatial stability of the data), but each stratum mean click rate is estimated independently for each year. The purpose of stratification is to statistically account for much of the inter-site variance in the number of clicks recorded; the number of strata was chosen subjectively, after exploratory data analysis.

Uninformative prior distributions were used for all model parameters. For each model, inference was performed using Markov chain Monte Carlo methods: a single chain was run for 1 010 000 iterations using the WinBUGS (geostatistical model) and OpenBUGS (mixture model) software packages (Lunn *et al.*, 2012), the first 10 000 samples were discarded and thereafter every 100th sample was retained for posterior distribution summaries, yielding 10 000 samples for each model. Results are reported separately for each model, but also combining samples from both to form a model-averaged estimate. Each model has equal weight in the model averaging.

### 2.3 Checking acoustic metric

For annual change in acoustic activity to represent change in abundance, there must be no systematic change in animal vocal behavior or range-specific click detection. Data were not available to measure these directly (e.g., through animal-borne recording tags); however, we searched for changes in the number of detected vaquita clicks in minutes when animals were known to be present (a measure of acoustic behavior), for trends in temperature (known to affect propagation) and a proxy for background noise. Details are given in the supplementary material.<sup>1</sup>

### 2.4 Abundance estimate for 2016

Vaquita population abundance was estimated from Bayesian analysis of a combined visual and acoustic survey, conducted in the fall of 2015, by Taylor *et al.* (2016). The posterior distribution for population size was well approximated by a lognormal distribution with mean 66 and standard deviation 33. To project the population forward from 2015 to 2016, 20 000 random samples were drawn from this lognormal distribution, and each sample was multiplied by a sample from the distribution of annual change in acoustic activity,  $\lambda_{2015-2016}$  from the trend models. Using November 2, 2015 (the midpoint of the visual survey) as the survey abundance date, the projected estimate represents population size on November 2, 2016.

## 3. Results

The sampling effort in 2016 was high for the 46 original sampling locations, with most C-PODs being operational for the entire core period [Fig. 1(A)]. As in earlier years, vaquita detections were restricted to only some portion of the refuge, with the highest click rates close to the southwest boundary; the additional 47 locations monitored for the first time in 2016 [Fig. 1(B)] make it clear that detections decline to almost zero on this boundary (and most other boundaries).

The recorded number of vaquita clicks per day in the 46 original locations decreased by 44% from 2015 to 2016 ( $\lambda_{2015-2016} = 0.56$ ). However, this statistic does not account for unequal sampling effort across sites. Results from the statistical models, which do account for an unequal effort, and give estimates of statistical uncertainty, are summarized in Fig. 2 (see also the supplementary material<sup>1</sup>). The values for 2011–2015 are very similar to those reported by Jaramillo-Legorreta *et al.* (2017), as would be expected since the addition of a sixth year of data should not change substantially results from the previous five. The estimated change in acoustic activity between 2015 and 2016 differs somewhat between the two models and has wide posterior CRIs; combining results from the two produces a model averaged posterior mean estimate of  $\lambda_{2015-2016} = 0.51$  with 95% posterior CRI 0.18 to 1.08. Although this interval includes the “no change” value of 1.0, the posterior probability that acoustic activity decreased between 2015 and 2016 [i.e.,  $p(\lambda_{2015-2016}) < 1.0$ ] is 0.96 (Fig. 3).

Another way to express the estimated change in acoustic activity is as a percentage rate of decline or increase  $(\lambda - 1) * 100$  (Fig. 2). The estimated model averaged

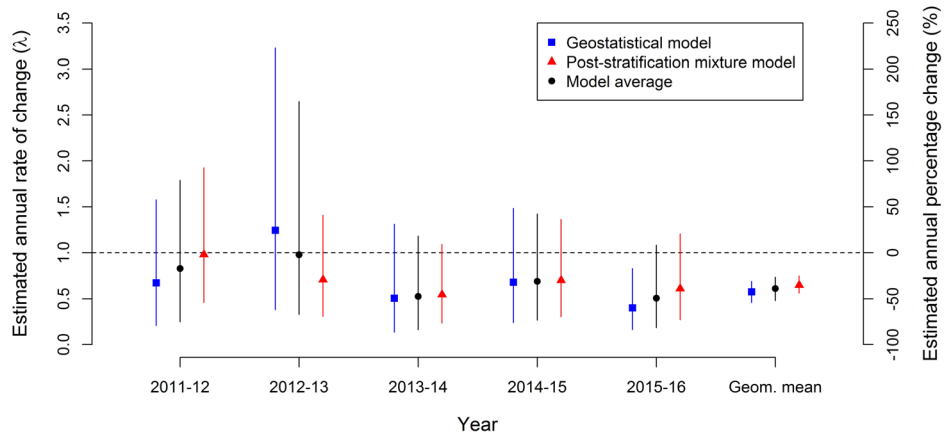


Fig. 2. (Color online) Estimated annual rate of change ( $\lambda$ ) and percentage change (%) in mean click rate from the statistical trend models. Solid symbols denote posterior means and vertical bars 95% posterior CRIs. “Geom. mean” is the geometric mean of the annual estimates.

percentage rate of decline between 2015 and 2016 was extremely high: posterior mean 49% decline (95% CRI 82% decline to 8% increase).

Over the entire monitoring period 2011–2016, the estimated average annual change in acoustic activity is 0.61 (95% CRI 0.48–0.74), i.e., an average decline of 39% per year (95% CRI 26% to 52%, Fig. 2). This corresponds to an estimated total decline of 90% over this 6-year period. The posterior probability of a decline is 1.00, and there is a >99% chance that the decline in acoustic activity has averaged >20% per year (Fig. 3).

The spatio-temporal pattern of estimated click rates from the geostatistical model is shown in Fig. 4. The spatial pattern of click rates is quite consistent between years, with the southwest area being a relative hotspot in all years. However, the strongest pattern is the overall steep decline in click rates over time.

No yearly change was found in the metric of acoustic behavior or background noise; water temperature generally increased over time, but the resultant effect on propagation loss is likely to be minimal (see the supplementary material<sup>1</sup>).

The projected population size estimate for November 2, 2016, using the model averaged acoustic results, is approximately 30 (posterior mean 33; posterior median 27; 95% CRI 8 to 96).

#### 4. Discussion

Despite the gillnet ban, there is a very high probability that acoustic activity within the vaquita refuge has continued to decline between 2015 and 2016. As expected, the estimate for annual change in acoustic activity for a single year (2015–2016) is too imprecise to say whether it differs either from the previous year (2014–2015) or from the series of years (2011–2015). Given the low number of acoustic detections, it will take several years of monitoring to pick up such changes in trend, although the augmented

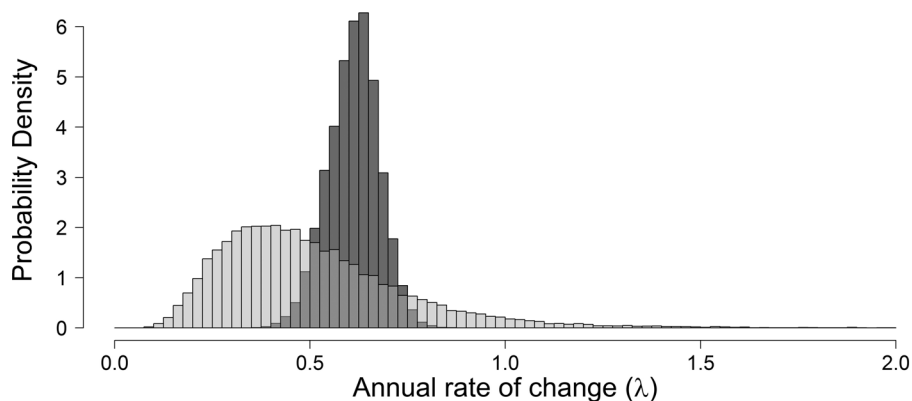


Fig. 3. Model-averaged posterior probability distribution for the annual rate of change in mean clicks-per-day. The darker gray distribution describes geometric mean annual rate of change from 2011 to 2016. The lighter distribution describes the change between 2015 and 2016. Values less than 1.0 indicate a decline, for example, a value of 0.5 indicates a halving each year.

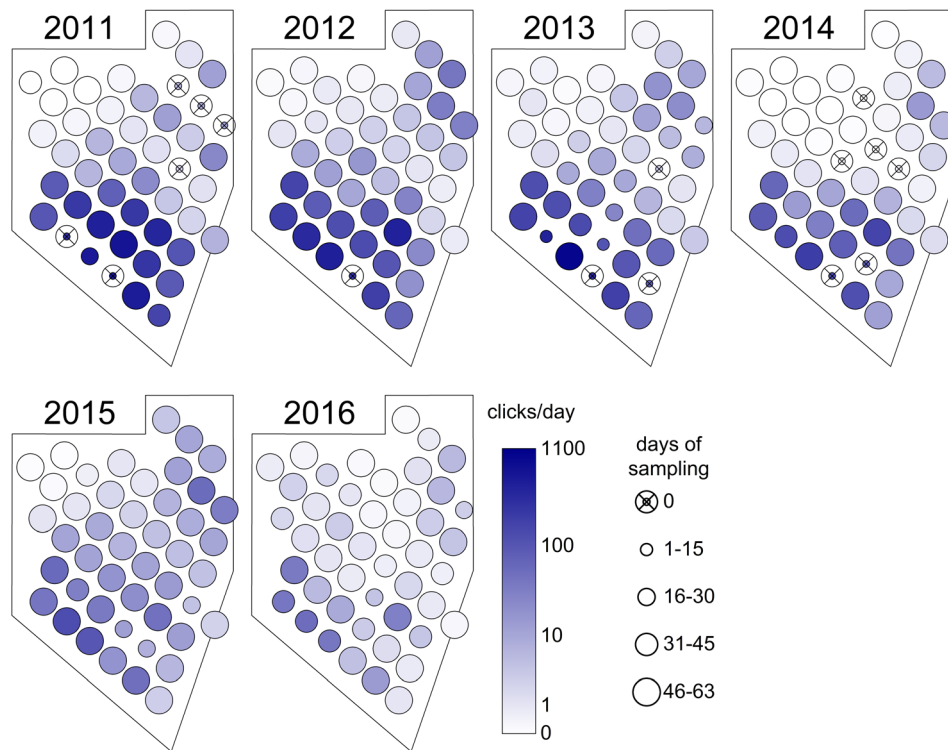


Fig. 4. (Color online) Estimated mean number of clicks per day predicted by the geostatistical model for the 46 numbered sampling sites with data for at least 1 year. Values in the legend are posterior medians (note log scale). Some sites, ⊗, were missing in the indicated year. The size of the circles indicate the number of sampling days on each year (see the legend).

monitoring design will help improve precision. There is little doubt, however, that the decline continues and is rapid.

Relating this decline in acoustic activity to a decline in population size requires the assumption that the acoustic behavior of vaquita and detection performance has not changed; our investigations (see the supplementary material<sup>1</sup>) provide partial validation of this. Another important assumption in extrapolating the trend observed in the vaquita refuge from acoustic data to total population trend is that population trend outside the refuge is the same as that inside. The combined visual-acoustic survey of Taylor *et al.* (2016) estimated that, in 2015, approximately 20% (12 of the estimated 59) of the vaquita population were outside the refuge. Hence, if the population change outside the refuge is different from that inside, it will have only a small effect on the overall trend, because it is only a small proportion of the total population. It is possible that animal distribution has changed radically between 2015 and 2016, with animals moving out of the refuge causing the observed decline. However, this seems very unlikely given low detections on the periphery of the range from the augmented grid [Fig. 1(B)] and the relative paucity of detections outside the refuge on previous synoptic surveys (e.g., Fig. 1 of Rojas-Bracho and Reeves, 2013).

If the acoustic change between 2015 and 2016 represents a population change, then we estimate that approximately 30 vaquita remained as of November 2, 2016. Only a fraction of these will be reproductive-age females. Given this estimate, and the ongoing negative population trend, it seems clear that we are facing the imminent extinction of this species unless radical and effective conservation measures are immediately implemented.

#### Acknowledgments

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### References and links

<sup>1</sup>See supplementary material at <https://doi.org/10.1121/1.5011673> for an investigation of the acoustic metric used and results summary table.

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# 1 **Supplementary Material for JASA Express Letters article**

## 2 3 **Last call: passive acoustic monitoring shows continued rapid** 4 **decline of critically endangered vaquita**

5  
6 **Len Thomas, Armando Jaramillo-Legorreta, Gustavo Cardenas-Hinojosa, Edwyna Nieto-**  
7 **Garcia, Lorenzo Rojas-Bracho, Jay M. Ver Hoef, Jeffrey Moore, Barbara Taylor, Jay**  
8 **Barlow and Nicholas Tregenza**  
9

### 10 **S1. Checking acoustic metric**

11 As stated in the main body of the paper, for annual change in acoustic activity to represent  
12 change in abundance, there must be no systematic change in animal vocal behavior or range-  
13 specific click detection. Although data were not available to measure these directly (such as  
14 from animal-borne acoustic and movement recording tags), we performed three checks using  
15 metrics related to acoustic behavior, sound propagation and background noise respectively.  
16 These checks augment those performed by Jaramillo-Legorreta et al. (2017, Supporting  
17 Information Appendix 1) on the 2011-2015 data, and by Taylor et al. (2016, Supporting  
18 Information Appendix 3) on a separate acoustic survey undertaken in 2015 over a wider area (as  
19 part of a combined visual-acoustic abundance estimation study).

20 For each check, we derived a relevant response variable, at the level of day within  
21 sampling location within year. We then averaged across days (using only the core period 19  
22 June to 19 August) to obtain a value per sampling location and year. We visually examined the  
23 distribution of values between years using a boxplot. We also fit a classical linear mixed model  
24 with year as a categorical explanatory variable and location as a random effect; by comparing  
25 this to a model with no year effect we derived an indication of whether the response variable



26 changed significantly between years. Analyses were performed using R 3.4.1 (R Core Team  
27 2017).

28 To help maintain comparability between years, only the 34 sampling locations that were  
29 sampled in all 6 years were included in the above analysis. We did not attempt to weight the  
30 models or boxplots by the number of sampling days in each location and year.

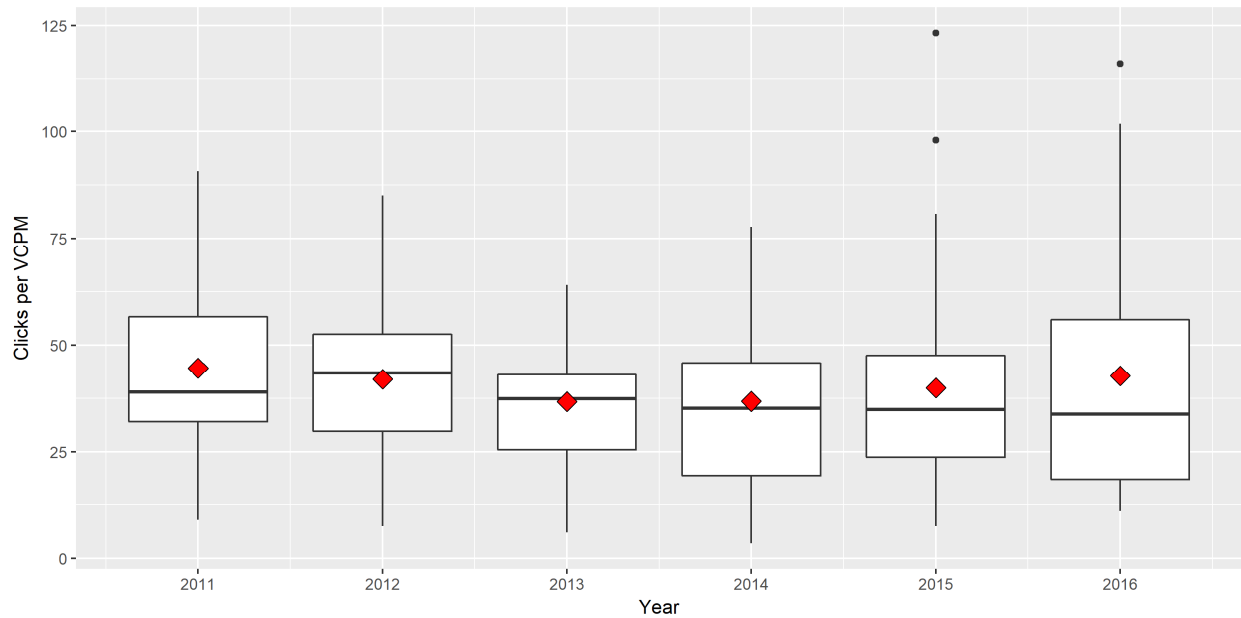
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### 32 **S1.1. Acoustic behavior**

33 If acoustic behavior changed over time, we would expect to see changes in the number of  
34 detected vaquita clicks when animals are known to be present. To check this, we grouped the  
35 acoustic data for each day and sensor location into “vaquita click positive minutes” (VCPMs) –  
36 i.e., minutes where at least one vaquita click train was detected. We then used as a response  
37 variable the number of clicks per VCPM. Note that, unlike the other two analyses reported here,  
38 sampling locations with no vaquita click detections in a year were necessarily excluded from the  
39 analysis, so the number of sampling locations was not the same in every year.

40 We found no evidence of change in clicks per VCPM between years, either from the  
41 boxplot (Fig. S1) or linear mixed model ( $\chi^2 = 4.24, df = 5, p = 0.49$ ). Note that this should  
42 not be taken as definitive evidence of no change – for example, if some animals stop  
43 echolocating entirely for extended periods in some years then this will not be detected using the  
44 above metric. However, we have no reason to expect such a change in acoustic behavior  
45 (vaquita are like harbor porpoises, which forage nearly continuously day and night – see, e.g.,  
46 Wisniewska et al. 2016). More direct measurements of behavior, such as from an animal-  
47 attached acoustic tag or a focal follow with acoustic array, are not feasible given the extremely

48 low population density and cryptic nature of the vaquita. We therefore cautiously conclude that  
49 change in acoustic behavior is unlikely to have caused spurious population indices.



50  
51 *Figure S1. Boxplots showing distribution of clicks per vaquita click positive minute (VCPM) at*  
52 *sampling locations between years. Bottom and top of the boxes indicate the first and third*  
53 *quartile; vertical line the median; red diamond the mean; horizontal lines (whiskers) the lowest*  
54 *and highest data point within 1.5 times the inter-quartile range of the lower and upper quartile,*  
55 *respectively; dots (outliers) any data points outside this range.*

56

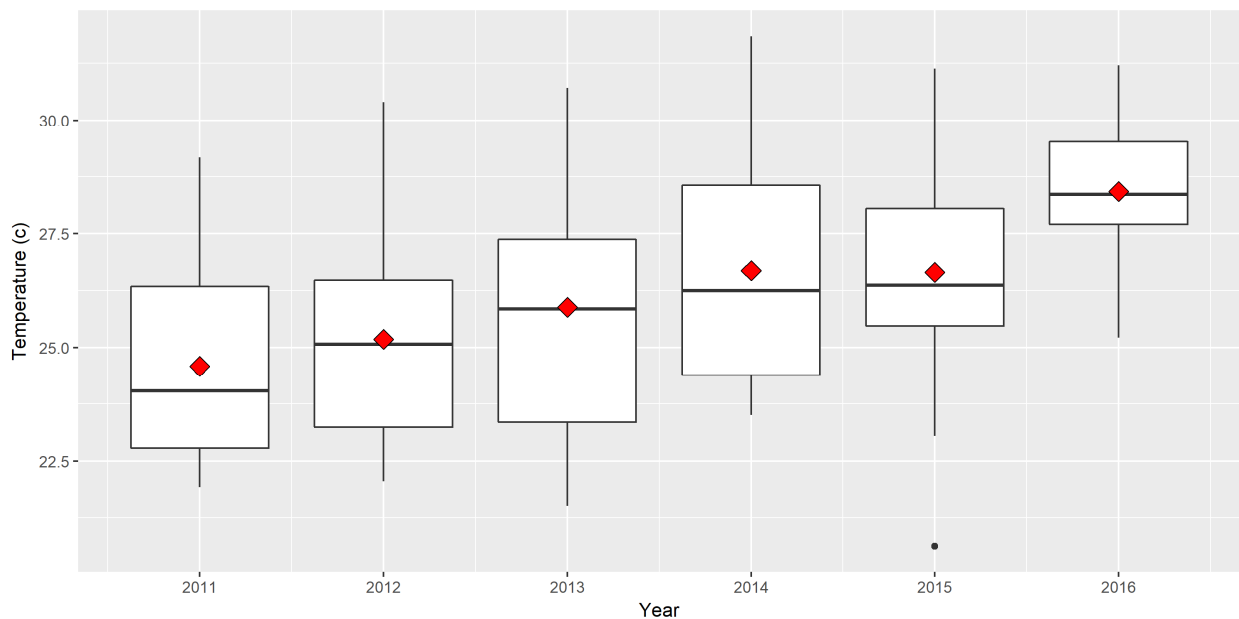
## 57 **S1.2. Sound propagation**

58 Range-specific sound propagation can be measured by playback experiments using artificial  
59 vaquita clicks; such an experiment was undertaken by Taylor et al. (2016) in 2015 over a wider  
60 geographic region than that sampled here, but that has not been repeated in other years. Taylor  
61 et al. were interested in spatial variation in propagation between the core area sampled here and a  
62 shallow region further to the north and west; they concluded that there may be small differences

63 in propagation, but that these are unlikely to be enough to cause large differences in effective  
64 vaquita click detection ranges (see Taylor et al. 2016 Supporting Information Appendix 3).

65 To minimize the effect of seasonal differences in propagation, the analyses were all  
66 restricted to same period of 19 June to 19 August, inclusive. Nevertheless, some factors  
67 affecting propagation may vary between years even within the same dates. One factor that we  
68 have measurements on is temperature – this is measured by the CPOD loggers every minute. We  
69 therefore used mean temperature as a response variable indicating possible changes in  
70 propagation conditions.

71 We found strong evidence for a change in temperature between years (Figure S2;  $\chi^2 =$   
72  $59.29, df = 5, p < 0.001$ ): mean temperature appears to have generally increased over time,  
73 with a strong jump between 2015 and 2016. The overall difference in mean temperature between  
74 2011 and 2016 is 4.0 degrees centigrade.



75  
76 *Figure S2. Boxplots showing distribution of temperature at sampling locations between years.*

77 To quantify the possible effect of such a change on transmission loss, we estimated the  
 78 transmission loss due to absorption (which is the component affected by temperature), using  
 79 equations 7.53a to 7.54c of Kinsler et al. (1982):

$$80 \quad a = \frac{A f_1 f^2}{f_1^2 + f^2} + \frac{B f_2 f^2}{f_1^2 + f^2} + C f^2$$

81 where  $a$  is the transmission loss per meter (dB),  $f$  is the frequency, assumed to be 135 kHz,  $f_1$  is  
 82 the relaxation frequency (Hz) of boric acid, calculated as

$$83 \quad f_1 = 1.32 \times 10^3 (T + 273) e^{-1700/(T+273)}$$

84 where  $T$  is the temperature (Celsius),  $f_2$  is the relaxation frequency (Hz) of magnesium sulfate,  
 85 calculated as

$$86 \quad f_2 = 1.55 \times 10^7 (T + 273) e^{-3052/(T+273)}$$

87 and  $A$ ,  $B$  and  $C$  are temperature- and pressure-dependent values calculated as follows.

$$88 \quad A = 8.95 \times 10^{-8} (1 + 2.3 \times 10^{-2} T - 5.1 \times 10^{-4} T^2)$$

$$89 \quad B = 4.88 \times 10^{-7} (1 + 1.3 \times 10^{-2} T) (1 - 0.9 \times 10^{-3} P_0)$$

$$90 \quad C = 4.76 \times 10^{-13} (1 - 4.0 \times 10^{-2} T + 5.9 \times 10^{-4} T^2) (1 - 3.8 \times 10^{-4} P_0)$$

91 where  $P_0$  is the pressure in atmospheres, assumed to be 2 (corresponding with a depth of  
 92 approximately 10m). Given a value of  $a$ , we estimated transmission loss due to absorption at a  
 93 nominal distance of  $r = 100$ m as

$$94 \quad TL_a = r a$$

95 These calculations (Table S1) yield a negligible decrease in transmission loss, from  
 96 4.605 dB at 24.6 °C in 2011 to 4.584 at 28.4 °C in 2016 – a change of only 0.021 dB. We  
 97 conclude that the warming Gulf has likely had little direct effect on the effective detection  
 98 distance of vaquita clicks.

Year	2011	2012	2013	2014	2015	2016	Unit
$T$	24.6	25.2	25.9	26.7	26.6	28.4	°C
$f_1$	1298.25	1315.90	1336.72	1360.80	1357.78	1413.01	Hz
$f_2$	162223	165939	170363	175539	174885	186971	Hz
$A$	1.13E-07	1.12E-07	1.12E-07	1.12E-07	1.12E-07	1.11E-07	
$B$	6.43E-07	6.47E-07	6.51E-07	6.56E-07	6.56E-07	6.67E-07	
$C$	1.77E-13	1.74E-13	1.71E-13	1.68E-13	1.68E-13	1.62E-13	
$a$	0.04605	0.04606	0.04605	0.04602	0.04602	0.04584	dB/m
$TL_a$	4.605	4.607	4.605	4.602	4.602	4.584	dB

*Table S1. Estimated transmission loss (Trans. loss) due to absorption for a 135 kHz signal at the mean temperature observed in each year of sampling. Symbols are defined in the text.*

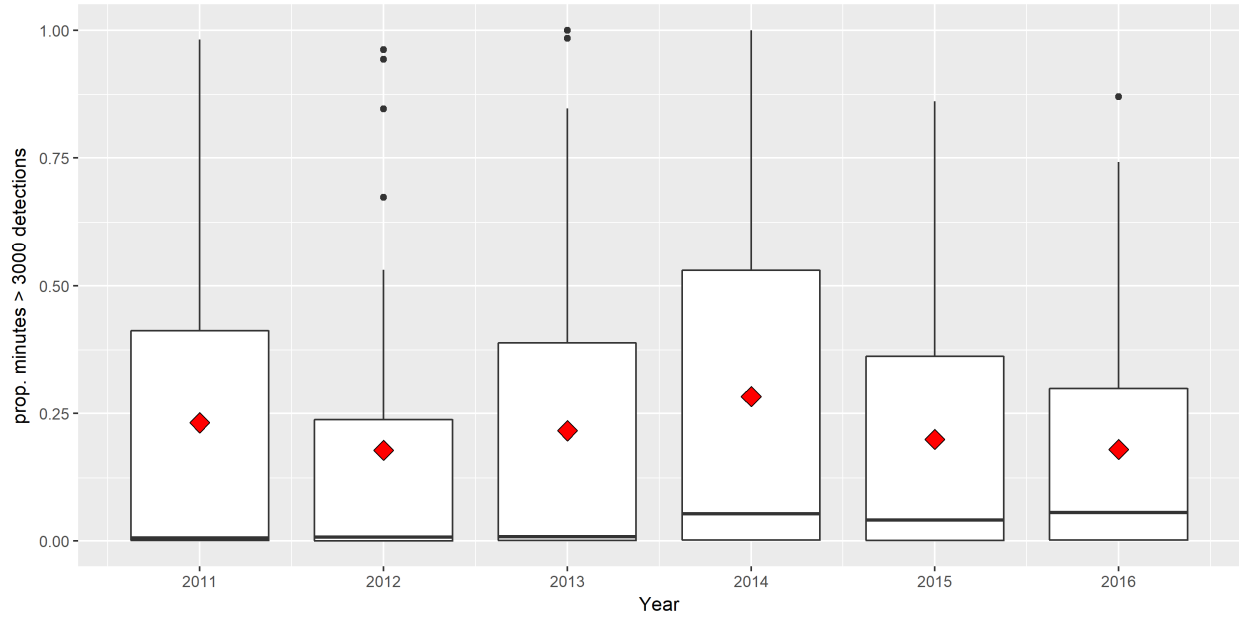
### 99 **S1.3. Background noise**

100 The vast majority of detections made by the CPOD logger are not vaquita clicks; rather they are  
101 impulsive sounds from other sources such as crustaceans and fine sand in suspension, and these  
102 are filtered out in post-processing, at the classification stage. These recorded sounds provide  
103 some opportunity to quantify background noise at vaquita-relevant frequencies, because the  
104 number of detections per minute of sampling effort will be related to the level of background  
105 noise. Taylor et al. (2016, Supporting Materials Appendix 3) used this approach to investigate  
106 whether there was a difference in background noise between core and shallow water strata.  
107 They found some differences between strata (the shallow stratum was noisier). This prompted a  
108 further investigation, where copies of real vaquita click trains were added to data sets of varying  
109 noise level, and the performance of the detection and classification algorithm in finding them

110 was assessed. There was no difference in detection performance in quieter conditions, defined as  
111 those with less than 3000 detections per minute, but some degradation of performance was noted  
112 in higher noise conditions (i.e., 3000 detections per minute or greater).

113 We therefore used as response metric the proportion of “noisy minutes” – i.e., minutes  
114 with >3000 detections. There was no evidence of a change in the proportion of noisy minutes  
115 between years ( $\chi^2 = 6.87, df = 5, p < 0.23$ ), although the data are strongly right-skewed  
116 (Figure S3) and so a more sophisticated analysis that does not assume a normally-distributed  
117 response may be warranted. Even so, the median (across sites) proportion of noisy minutes was  
118 less than 0.06 in all years, meaning that most sites do not have high levels of background noise  
119 most of the time. Note that fishing activity is unlikely to contribute strongly to background noise  
120 because the season for acoustic monitoring was chosen because summers generally have very  
121 low fishing effort (including for Totoaba, which spawn in winter/spring).

122 We conclude that background noise variation between years is unlikely to bias the  
123 estimated changes in vaquita population size.



124

125 *Figure S3. Boxplots showing distribution of proportion of “noisy minutes” – i.e., minutes with*

126 *>3000 detections at sampling locations between years.*

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*Table S1. Estimated annual rate of change ( $\lambda$ ) in acoustic activity from the statistical trend models. Quantities are posterior means with 95% posterior credible intervals in brackets.*

Year	Geostatistical model	Post-stratification mixture model	Model average
2011-12	0.674 (0.207-1.578)	0.980 (0.460-1.927)	0.827 (0.250-1.791)
2012-13	1.244 (0.381-3.230)	0.708 (0.309-1.409)	0.978 (0.329-2.647)
2013-14	0.505 (0.136-1.311)	0.546 (0.236-1.091)	0.525 (0.162-1.182)
2014-15	0.680 (0.241-1.485)	0.702 (0.304-1.364)	0.691 (0.267-1.423)
2015-16	0.401 (0.163-0.827)	0.611 (0.270-1.206)	0.506 (0.184-1.083)
Geometric mean annual change	0.575 (0.460-0.691)	0.649 (0.562-0.749)	0.612 (0.480-0.735)