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More vaquita porpoises survive than expected

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ABSTRACT: In 2018, it was estimated that fewer than 20 of Mexico's endemic vaquita porpoise *Phocoena sinus* remained, and the species was declining by 47% yr^{-1}. Entanglement in gillnets is the sole threat to the species, and since the last population size estimate, gillnetting has increased in the small area where most vaquitas remain — a 12 × 24 km area in the Gulf of California near San Felipe, Mexico. We conducted research efforts in 2019 and 2021 in that area to estimate the minimum numbers of adults and calves and look for any signs that vaquitas are unhealthy. Through expert elicitation, we estimated between 7 and 15 unique individuals were seen in 2019 and 5–13 were seen in 2021. Calves were seen in both years, and all vaquitas appeared healthy. Population projections from the last full survey indicated that more vaquitas have survived than expected. We suggest that these surviving adult vaquitas may have learned to avoid entanglement in gillnets. These vaquitas and their calves provide hope that the species can survive. However, given the high levels of illegal gillnetting and the theft of equipment which hindered our monitoring efforts, and with only around 10 individuals remaining, survival can only be assured if vaquita habitat is made gillnet-free.

KEY WORDS: *Phocoena sinus* · Vaquita · Conservation · Endangered species · Behavioral selection · Monitoring small populations · Expert elicitation · Illegal fishing · Porpoise

1. INTRODUCTION

The vaquita porpoise *Phocoena sinus* is a naturally rare species endemic to Mexico that numbered from 2000–5000 individuals for hundreds of thousands of years (Taylor & Rojas-Bracho 1999, Morin et al. 2021, Robinson et al. 2022). Vaquitas are, however, now being driven towards extinction through incidental death in gillnets (for a review see Rojas-Bracho & Reeves 2013). Vaquitas become entangled in all types of gillnets, including those set for shrimp and finfish, but those set for totoaba *Totoaba macdonaldi*, a fish similar in size to vaquita, are most lethal (Vidal 1995). The resumption of illegal totoaba fishing around 2010 (EIA 2016) resulted in a catastrophic decline of vaquitas (Jaramillo-Legorreta et al. 2017, Taylor et al. 2017, Thomas et al. 2017). Based on acoustic monitoring, the rate of decline between

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2017 and 2018 was estimated to be 47% yr^{-1} (95% Bayesian credible interval [CRI]: 80% decline to 13% increase), and fewer than 20 individuals were estimated to remain in 2018 (Jaramillo-Legorreta et al. 2019). Acoustic data also revealed a substantial reduction in the area used by the remaining vaquitas: nearly all detections were in a small area off the town of San Felipe, Mexico. Since 1997, the vaquita recovery team (Comité Internacional para la Recuperación de la Vaquita [CIRVA]) has provided conservation advice at the request of the Government of Mexico. In 2019, CIRVA recommended that the small area in which most vaquitas are found (12 × 24 km), called the Zero Tolerance Area (ZTA), receive the focus of enforcement efforts (CIRVA 2019), and the Government of Mexico passed a regulation in 2020 prohibiting any fishing in the ZTA (DOF 2020).

The decline in vaquita population size has been well documented. The first survey to cover the full vaquita distribution, conducted in 1997, used visual line-transect methods (Jaramillo-Legorreta et al. 1999). This effort noted the difficulty in sighting this species because of small group sizes, inconspicuous surfacing, and avoidance of the survey vessels. Imprecise population size estimates raised concerns about timely detection of potential population declines (Taylor & Gerrodette 1993). Acoustic monitoring methods were developed to increase precision of estimating both population size and trends in population size (Jaramillo-Legorreta et al. 2017), and a combination of visual and acoustic methods was used to estimate vaquita population size in 2008 (Gerrodette et al. 2011) and 2015 (Taylor et al. 2017). Between 1997 and 2015, the species declined by 92% (95% CRI: 80–97%; Taylor et al. 2017). The 2018 population size estimate was derived by projecting from the 2015 population size estimate using the distribution of the annual rate of change derived from the 2016–2018 acoustic data. Some of the numerical simulations resulted in population sizes lower than 7 vaquitas in 2017 or 6 vaquitas in 2018 (the minimum number known alive in those years); hence, these estimates were eliminated from the posterior distribution. Eliminating this portion of the distribution resulted in a revision of the 2015 estimate upwards, from the original posterior mean of 60 vaquitas to a new value of 100 (Jaramillo-Legorreta et al. 2019), showing the value of obtaining minimum estimates of population size.

Recent developments, however, have made both acoustic monitoring and visual line-transect methods difficult. Illegal fishers have removed the acoustic detectors (C-PODs, manufactured by www.chelonia.co.uk) used to record vaquita echolocation clicks. Stolen detectors are expensive to replace and the data are lost and irreplaceable. Unless enforcement of the fishing ban is effective and the theft of equipment is stopped, acoustic monitoring of the vaquita population using previously successful methods is no longer feasible. Alternative approaches may therefore be necessary for future monitoring.

Visual line-transect methods face a different problem. Estimating population size requires estimating the probability of detection as a function of distance, which in turn requires several dozen sightings (Buckland et al. 2015). The vaquita population size is now so low that this number of sightings would be extremely difficult to obtain. An alternative would be to use a previously obtained detection function — for example, that estimated from previous line-transect surveys using the R/V 'David Starr Jordan' (renamed R/V 'Ocean Starr') (Taylor et al. 2017). However, chartering this vessel and hiring experienced observers for the necessary time for a full survey would cost over US $3 million $survey^{-1}$. Because such funds for a full survey were not available, the size of the 2021 vaquita population could not be estimated using line-transect methods.

Mark–recapture using photographic identification is another method to estimate population size. Photographic identification of vaquitas began in 2008 (Jefferson et al. 2009), and opportunistic photographs were obtained during the 'VaquitaCPR' (CPR: conservation, protection, recovery) effort in 2017 (Rojas-Bracho et al. 2019a) and during a dedicated effort to obtain a vaquita biopsy on 24–28 September 2018. Although no within-year photo-recaptures were obtained, this survey provided photographic matches to photographs from 2017 that showed vaquitas could calve annually (Taylor et al. 2019), and a minimum of 6 animals seen on a single day helped inform the 2018 population size estimate (Jaramillo-Legorreta et al. 2019).

An additional reason for determining the minimum numbers of vaquitas remaining is to dispel assertions that the species is doomed or even already extinct. Field research was undertaken in 2019 and 2021 with the following objectives: to evaluate whether vaquitas still exist, to estimate the minimum number of vaquitas remaining (those seen within the ZTA), to assess their recovery potential by also estimating the number of calves seen, and to look for any signs that animals were in poor body condition. Passive acoustic monitoring was used to obtain locations of vaquitas within the recent periods (ranging from days to weeks depending on weather conditions and the chances of losing detectors to theft), and visual surveys were then undertaken to locate vaquitas and photograph them. The lack of within-year photographic recaptures in 2018 showed that estimating population size with mark–recapture methods would be unlikely to succeed. As a result, starting in 2019, the authors of the present study used expert elicitation (EE), which is a formal technique whereby probabilistic distributions on quantities of interest can be derived from expert judgment.

EE was first developed in the 1950s and 1960s (Brown 1968, O'Hagan et al. 2006). The technique translates information obtained from multiple experts into quantitative statements while minimizing bias in the elicited information and describing uncertainty. This technique is now widely applied to address conservation and management issues where there is a relative lack of data to inform decision making (MacMillan & Marshall 2006, Aspinall 2010, Knol et al. 2010, Runge et al. 2011, Martin et al. 2012, European Food Safety Authority 2014, Sivle et al. 2015). EEs have been conducted in marine mammal research and conservation in recent years (Booth et al. 2016, Tollit et al. 2016, Booth & Heinis 2018, Booth & Thomas 2021, Schwacke et al. 2021).

For the 2019 and 2021 surveys, we used EE to address 2 questions: (1) How many unique individual calves were sighted during each survey, and (2) How many unique individual vaquitas (including adults, juveniles, and calves) were sighted during each survey? With distributions for the number seen in the ZTA in both 2019 and 2021, we also addressed the question of whether the decline of approximately 50% yr^{-1} estimated in 2018 has continued. Illegal fishing for totoaba has continued since 2018 during the totoaba spawning season, which is concentrated between December and May (Cisneros-Mata et al. 1995). Furthermore, removal of illegal nets by the Sea Shepherd Conservation Society and the Museo de la Ballena was strong in 2016, 2017, and 2018 but was greatly curtailed in both 2019 and 2020 (reports available at https://iucn-csg.org/). Attacks by groups of local small-scale fishers resulted in the Mexican Navy asking the net-removal ships to leave the area. In addition to totoaba gillnetting, fishers also gillnet for shrimp and other finfish. We present no data on finfishing activities because vaquita visual research takes place in the fall during shrimp season, outside the finfish season. We observed no gillnetting inside protected vaquita areas in 2008, 2015, or 2017 (Gerrodette et al. 2011, Taylor et al. 2017, Rojas-Bracho et al. 2019a, respectively). In contrast, substantial gillnetting was observed within the ZTA in both 2019 and 2021, and fishers did not attempt to disguise their illegal activity (for examples of numbers and locations of boats see Rojas-Bracho et al. 2019b, 2021). Thus, gillnetting within the small area where vaquitas remain has increased from at least 2019 onwards.

2. MATERIALS AND METHODS

2.1. Survey methods

Surveys were conducted with 2 ships: R/V 'Narval' (7.7 m observer eye height) and either M/V 'Sharpie' or M/V 'Farley Mowat' (8.1 m observer eye height). Each ship was equipped with 2 sets of high-powered deck-mounted binoculars (25 × 100 mm) used by experienced vaquita observers. Data were recorded in a field laptop using software with GPS input and a digital compass to provide a real-time map of vaquita detections so as to improve chances of tracking vaquitas for photographing. Locations of vaquita sightings were calculated using reticles in the binoculars, GPS position, ship heading, and observer eye height. Methods were similar in 2019 (18 d of survey time beginning 3 September and ending 27 October) and 2021 (17 d of survey time beginning 17 October and ending 3 November). Both efforts were guided by passive acoustic data that indicated nearly all vaquita detections were within the ZTA and concentrated in limited areas (see Text S1 in the Supplement at www.int-res.com/articles/suppl/n048p225_supp.pdf).

Typically, the 2 ships traversed lines following the grid of acoustic detectors, staying about 2–4 km apart and striving to maintain speeds between 7.5 and 13 km h^{-1}. Ships stayed close together to allow both ships to converge when a vaquita sighting was made. Once vaquitas were sighted, both ships were brought within 1–2 km of the sighting (visible on a map on the computer monitor), and all 12 observers (6 observers $ship^{-1}$) were deployed on the flying bridges to track vaquitas and obtain photographs and videos. If tracking was successful and the animals did not behave evasively, small vessels were launched (typically 1 vessel $ship^{-1}$) with photographers to increase the chances of obtaining photographs of sufficient quality to identify individuals.

2.2. EE methods

EE workshops were held remotely from 31 August through 3 September 2020 (eliciting on the 2019 survey) and on 4 and 19 November 2021 (eliciting on the

2021 survey). The experts were those who had participated in the surveys in each year. Experts were informed of the purpose of the elicitation, and informed consent was obtained from all participants involved in the study (aligned with the framework outlined in 45 CFR available at https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html). In advance of the EE workshop, experts completed an online e-learning course designed to train them through a series of lectures and practical exercises in subjective probabilities, distributions, and making reasoned probabilistic judgments. The elicitation process broadly followed that of the Sheffield Elicitation Framework (SHELF; Gosling 2018), as detailed below. The EE was facilitated by a trained, experienced facilitator (C.B.) with support from a statistical specialist (L.T.). The facilitator managed discussions to help avoid common biases that can arise (Aspinall 2010). Evidence dossiers (short reports giving the relevant background information) were prepared for each EE and made available in advance to the experts. These dossiers contained detailed descriptions for each sighting (including estimates of numbers of animals in each sighting, movement information, and photos/videos where available). When vaquitas were seen by both ships, observer drawings of the location of animals with respect to the ship were sometimes added as well as reconstructions of the position of ships and vaquitas using data from both ships. Summaries of the evidence dossiers are given in Text S2; full versions are available on https://iucn-csg.org in the 2019 and 2021 EE reports.

For each survey, 2 quantities of interest (QoIs) were elicited: (1) How many unique individual calves were sighted, and (2) how many unique individual vaquitas (including adults, juveniles, and calves) were sighted? In essence, the experts were being asked how many animals were resights within the given year. For each question, the elicitation proceeded in 2 stages. First, experts were asked independently to provide their judgments on each question (see below for details). The set of elicited probability distributions from the experts was presented back to the group, initially in an anonymized form, and experts were then invited to justify their judgments, particularly those that were divergent, to ensure that the range of judgments was discussed openly. Second, we used a group process to reach consensus via the 'rational impartial observer' (RIO) approach (Gosling 2018), as follows. Experts were asked to discuss and agree upon a probability distribution which would represent the reasoned opinions of a hypothetical external observer, called the RIO, who was party to all of the information and discussions that had taken place. It was highlighted that the RIO would not have identical views to any one of the experts but would instead find some merit in all the differing arguments or justifications — and give some weight to each.

Details of the EE methods differed slightly between 2020 and 2021. In 2020, in the first stage of the elicitation, experts provided individual judgments on plausible upper and lower limits and (potentially non-integer) quartiles for each QoI. The plausible limits were defined such that it may be theoretically possible for the true value of the QoI to lie outside these limits, but the expert would regard it as extremely unlikely that the QoI was outside this range. The individual expert judgments were fitted to a suite of continuous probability distributions using the package SHELF (Oakley 2020), accessed from the statistical software R version 4.1.2 (R Core Team 2021). The distributions that best fitted the elicited quantiles were selected using a least-squares algorithm on each distribution's cumulative distribution function (candidates: normal, *t*, shifted gamma, lognormal, log-*t*, shifted scaled beta). A linear pool of these distributions was used as the starting point for the second, behavioral aggregation stage (see O'Hagan et al. 2006, Chapter 9). Linear pooling is a method of combining experts' distributions, giving equal weight to each. A shifted scaled beta distribution was fitted to the linear pool, and its parameters were manually adjusted, using a custom-written interactive R package ('shiny'; Chang et al. 2020) that gave graphical feedback on the distribution, until experts agreed it represented the RIO consensus distribution.

In feedback from the 2020 EE, participating experts commented that specifying quartiles was difficult when only a small number of integer values was possible. Therefore, for the 2021 EE, experts were asked instead to assign probability points ('probs') among integer values. Experts chose plausible limits and distributed 40 probs among the plausible integer values. A linear pool of these probs was created as the starting point for the behavioral aggregation stage, and the probs were then adjusted until experts agreed they represented the RIO consensus distribution.

2.3. Analysis of change in the rate of vaquita decline

Jaramillo-Legorreta et al. (2019) estimated that the number of vaquitas alive in autumn 2018 was 9 (posterior mean; posterior median: 8; 95% CI: 6–19). This number was derived by projecting forward 10 000 samples from the estimated population size distribution from the 2015 visual acoustic population survey according to the changes in acoustic detections between 2015–2016 (57% decrease; 95% CI: 19–80% decrease), 2016–2017 (48% decrease; 95% CI: 78% decrease to 9% increase), and 2017–2018 (47% decrease; 95% CI: 80% decrease to 13% increase). The projection also accounted for the observed minimum number alive (based on sightings) of 7 in 2017 and 6 in 2018. To determine whether it is plausible that this rate of decline has continued, we took the posterior distribution of number alive from 2018 and projected forward to 2021 using a stochastic model.

When populations become very small, seemingly random variation in survival and birth rates around their average values (demographic stochasticity) can dominate the population dynamics. The vaquita population is very small, and hence it is possible that even if we assume the expected rate of population decline from 2018–2021 is equal to that from 2017–2018, by chance a higher number of animals may have survived than expected, resulting in a minimum number alive that is compatible to the 2017–2018 trend. To examine this possibility, we undertook a population projection from 2018–2021 using a stochastic population model. Full details are given in Text S3, but in summary, the model was age- and sex-structured, assuming a female age at first reproduction of 5 yr, inter-breeding interval of 1.5 yr, expected 50:50 sex ratio at birth, calf survival 0.3 that of adult (age 5+) survival, juvenile (age 1–4) survival 0.95 that of adult survival, equal age-specific survival rates between sexes, and no reproductive or survival senescence. These assumptions yield a population with an expected age structure where 31% of the population are calves, 27% juveniles, and 42% adults, and an expected sex structure where 50% are females (see Text S3). In total, 10 000 realizations were generated, in each case sampling an expected rate of decline from the posterior distribution for 2017–2018, setting adult survival so that the equivalent deterministic population trajectory matched this rate of decline, initializing the 2018 population by sampling from the posterior population size in 2018 of Jaramillo-Legorreta et al. (2019), determining age- and sex-structure by sampling from a multinomial distribution with expected proportions in each age- and sex-class as given above, and then projecting forward stochastically assuming that both survival and reproduction were binomial processes (with the constraint that there must be at least one male for females to breed). For each realization, we used the EE distributions to determine the probability that the projected total population size is greater than or equal to the elicited minimum number alive. We then took the mean probability across realizations.

3. RESULTS

3.1. Survey

In 2019, surveys took place from 2–6 September and 15–27 October. In 2021, the survey took place between 17 October and 3 November. Both years lost most days to winds that were too high to sight and track vaquitas (greater than 13 km h^{-1}), but still obtained good coverage of the area (Text S1).

There were 24.0 h of surveys in low-wind conditions in 2019 and 51.6 h in 2021. However, for estimating minimum numbers of vaquitas seen, hours on the trackline poorly capture how minimum numbers are best obtained. Estimating the number of unique vaquitas seen is strongly influenced by the following factors: (1) whether multiple sightings are made on a single day, (2) whether sightings are of sufficient quality and duration to obtain photographs or good descriptions that allow observers to determine which sightings are resights, and (3) whether there are groups of more than the typical 2 vaquitas.

In 2019, there were 3 d with multiple sightings plus 2 sightings with excellent quality photographs that allowed individual identification (and matches to previous years). Both of the sightings from which good photographs were taken lasted more than 45 min. On 2 occasions there were also groups of 4, one that could have been 2 cow/calf pairs and one that had one cow/calf pair and one adult pair.

In contrast, 2021 had no sightings that lasted longer than 26 min, and not a single high-quality photograph was obtained. There were multiple sightings on only one day, and the largest group size seen was 3 individuals. The average sighting length in 2021 was 15.7 min compared to 26.1 min in 2019. These factors contributed to more uncertainty in the 2021 estimates than the 2019 estimates. In both years, all animals that could be seen well appeared robust, including calves.

Both surveys were hindered by the presence of many illegal fishing boats with gillnets in the water. Some areas could not be surveyed at all on some days due to the density of illegal fishing. Important location information from acoustics was also eliminated from much of both years due to loss of detec-

Fig. 1. Vaquita pair in front of a shrimp fishing boat setting gillnets within the Zero Tolerance Area in 2019

tors in areas of high fishing activity. Vessels had to maneuver around gillnets so that researchers could track vaquitas and obtain photographs (Fig. 1).

3.2. EE

For the 2019 survey, the final elicited distribution indicated that 3 was the most likely integer value for the number of calves sighted, with approximately equal belief that the true value was between 1 and 3 or between 3 and 5 calves. There was a 97 % chance of 2 or more calves and a 71 % chance of 3 or more. In 2021, the median of the elicited distribution for number of calves seen was 1.5, with approximately equal probability that 1 or 2 calves were seen. Overall, the EE results suggested that the number of calves seen in the ZTA decreased between 2019 and 2021 (Fig. 2).

The elicited distribution for the 2019 survey indicated that it was implausible that the true number of vaquita sighted was less than 7 or more than 15. The most likely value was 11 but values close to 11 were almost as likely. The distribution indicated an 84 % belief that the true number of unique vaquita sighted was between 9 and 13. For the 2021 survey, the distribution indicated that it was implausible that the true number of vaquitas sighted was less than 5 or more than 13, and that the most likely values were 7 and 8. The final distribution indicated a 78 % belief that the true number of unique vaquitas sighted was between 6 and 10. Thus, estimates for the total number of unique vaquitas seen in the ZTA suggested a small decrease between 2019 and 2021 (Fig. 3).

3.3. Analysis of rate of change

The projected distributions of population sizes for 2019 and 2021, assuming an expected rate of population decline equal to that estimated for 2017–2018, were generally much lower than the minimum population sizes elicited during the EE (Fig. 4). The mean probability that the projected population was greater than the minimum population size was 0.06 in 2019 and 0.07 in 2021.

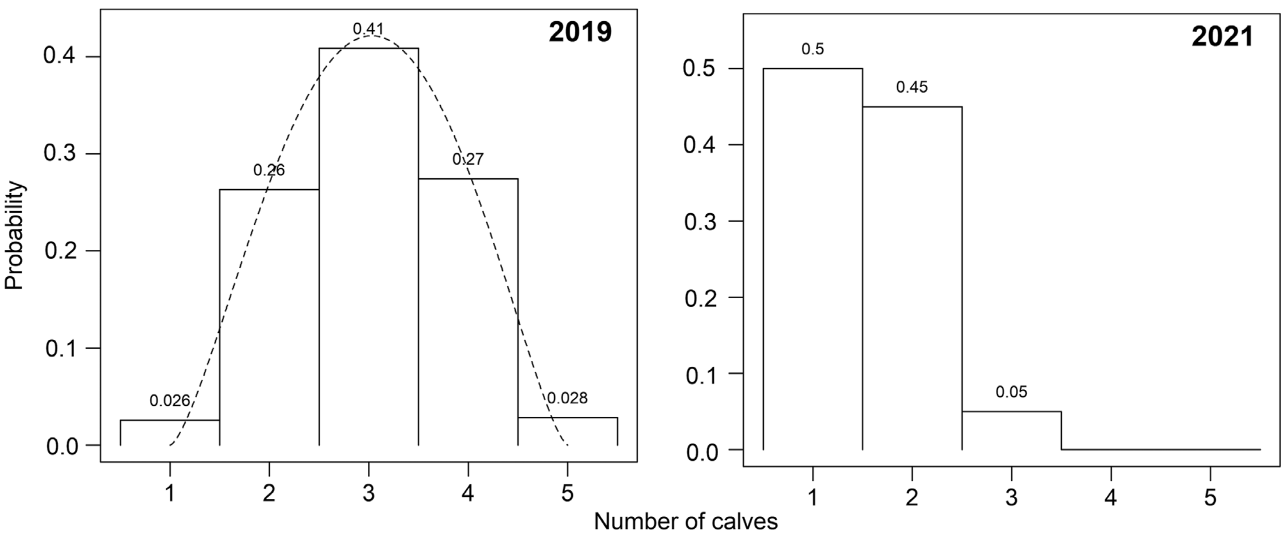

Fig. 2. Elicited distributions for number of vaquita calves sighted during 2019 and 2021 surveys. Values above histogram bars show probability of the corresponding number of calves. For 2019, the dashed curve shows the fitted scaled shifted beta distribution and the histograms show the area under the curve within ±0.5 of each integer value

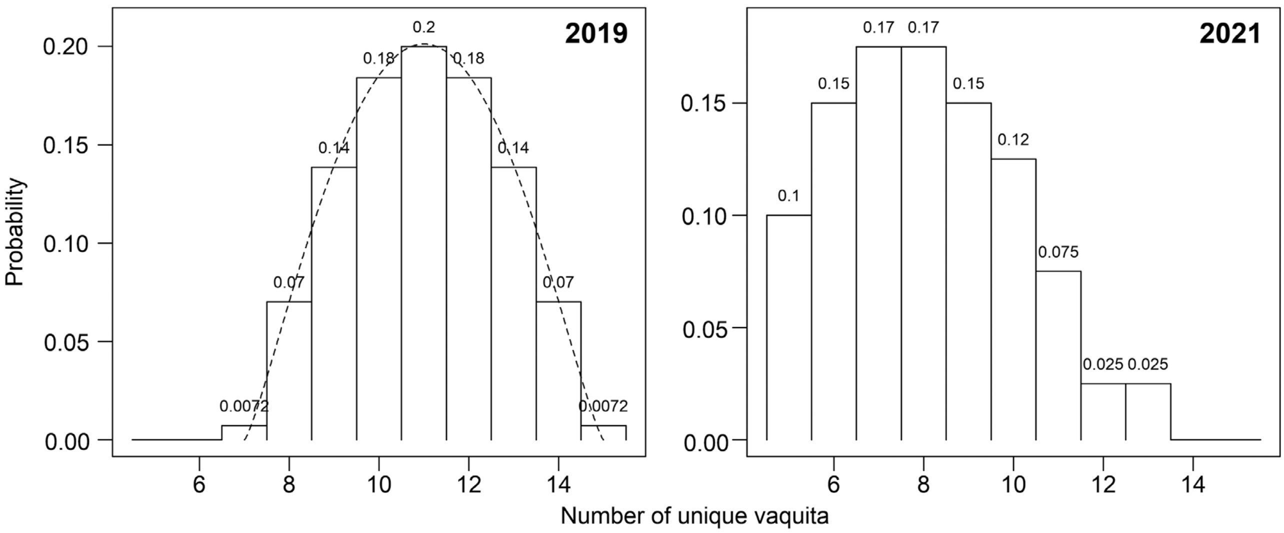

Fig. 3. Elicited distributions for total number of vaquitas sighted during 2019 and 2021 surveys. Values above histogram bars show probability of the corresponding number of vaquitas. For 2019, the dashed curve shows the fitted scaled shifted beta distribution and the histograms show the area under the curve within ±0.5 of each integer value

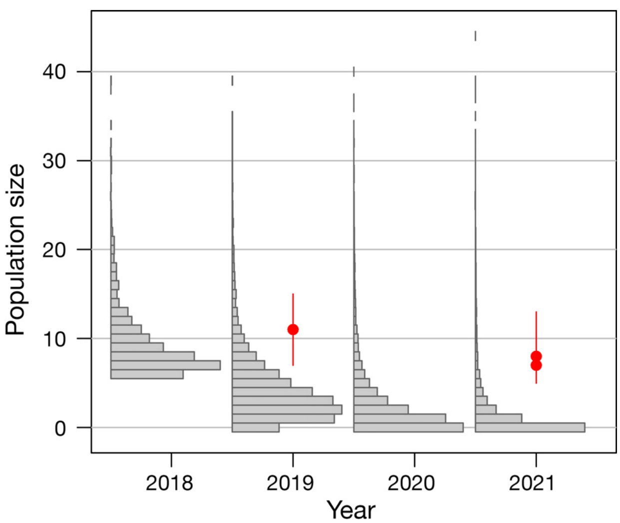

Fig. 4. Projected distribution of number of vaquitas from 2018–2021 assuming the expected rate of decline observed in 2017–2018 continued each year thereafter but projecting forward using an age- and sex-structured population dynamics model that includes demographic stochasticity. Red vertical lines: plausible range for the total number of vaquitas seen during the 2019 and 2021 surveys based on expert elicitation; red dots: most likely values (7 and 8 were judged equally likely for 2021). The number can be taken as an estimated minimum number alive

4. DISCUSSION

The limited surveys completed in 2019 and 2021 provided useful insights into the status of vaquitas. First, calves were seen in both years, and all animals appeared healthy. Examination of the genome of vaquitas has suggested that they have been a naturally rare population of about 2000–5000 breeding individuals for hundreds of thousands of years (Morin et al. 2021, Robinson et al. 2022). The low genetic diversity of vaquitas results from this natural rarity, and examination of the genome suggests purging of deleterious genes has reduced the potential negative effects of inbreeding. Population viability analyses using these empirical data suggest a high chance of recovery if vaquita bycatch is eliminated even if only 10 animals remained (Robinson et al. 2022). The observation of continued calving and observed robust animals is consistent with these genetic results.

Second, numbers of vaquitas do not appear to be declining at the rate observed earlier, despite recent high levels of illegal gillnetting within their last stronghold. Photographic identification has been possible because of nicks and scarring of dorsal fins. During the 2017 attempts to capture vaquitas (Rojas-Bracho et al. 2019a), animals were seen to actively avoid nets, and one animal from the entangled pair of vaquitas was observed to briefly become entangled and escape from the net. The other entangled vaquita later died from capture myopathy (Rojas-Bracho et al. 2019a). Post-mortem examination of the 15 yr old female killed in that attempt revealed multiple linear scars and fluke/fin notches typical of healed previous entanglement injuries (Rojas-Bracho et al. 2019a). It is plausible that the dorsal fin markings are the result of previous entanglements and that the surviving vaquitas have been behaviorally selected to be especially careful around gillnets.

Another possible reason that there are more vaquitas than expected is that the 2018 estimate was still negatively biased. The minimum numbers used to correct both the 2015 and 2018 estimates were numbers of animals known to be alive (for example, 6 vaquitas seen simultaneously in 2018). It is likely that if an EE effort similar to those done in 2019 and 2021 had been done in 2018, the minimum numbers used would have been higher than the number seen simultaneously. Thus, it is likely that the discrepancy between the predicted distribution of the vaquita population seen in Fig. 4 and the minimum numbers estimated from research in 2019 and 2021 results from a negative bias in the 2018 population size estimate. However, we emphasize that the projected values in Fig. 4 are for the total population size of vaquitas, while our 2019 and 2021 estimates are for the number seen within the ZTA. That the minimum estimate is still above the mean projected population size suggests a greater probability that vaquitas remain at numbers from which other species have recovered (Goodall 2009). Whether the surprising number of remaining individuals results from behavioral selection or unaccounted for negative bias in population size estimates or some combination of the 2 will never be known, but the unexpected result is only known because monitoring of the very small population continued.

Both the finding of a healthy genome and the potential role of behavioral selection in a critically endangered species have important implications for conservation biology. The Latin name for vaquita, *Phocoena sinus*, derives from the species being isolated in the far north of the Gulf of California, which is home to other endemic species. In the marine realm, the northern Gulf is essentially a habitat island. There are many similarly naturally rare species that live on actual islands (Robinson et al. 2016, 2018) or habitat islands that have also been isolated for thousands of years that may also be robust to inbreeding depression as a result of natural rarity, defined here as population sizes in the low thousands of individuals persisting for at least hundreds of generations. Using recently developed genomic techniques, vulnerability to inbreeding depression should be routinely examined for such naturally rare species (Morin et al. 2021, Robinson et al. 2022).

Similarly, behavioral selection in species exposed to strong single threats may increase the time available to eliminate threats and thus improve the chances of avoiding extinction. For species with a prolonged mother/offspring learning period, behavior could change the rate of decline. On the other hand, since the period of close contact of mothers with calves is less than 1 yr for vaquitas, it cannot be assumed that young vaquitas will learn to avoid gillnets to the extent that gillnets no longer pose a threat to their future existence. A few photographs and one video on social media of dead entangled vaquitas have appeared in the past few years, confirming the ongoing threat of gillnets to the species. The most prudent interpretation of the potential behavioral selection is that even experienced porpoises still make mistakes and die in gillnets, but that the few who have learned how to avoid entanglement may buy time for needed conservation actions to make their habitat gillnet-free.

The apparent decrease in the rate of decline once vaquita reached a very small population size does not negate the potential that small populations face accelerating rates of decline due to the self-reinforcing and synergistic effects called the 'extinction vortex', where demographic and environmental stochasticity combined with inbreeding depression and Allee effects hasten the descent to extinction (Gilpin & Soulé 1986). A retrospective study of 10 well-documented vertebrates that declined to extinction found corroborative evidence for the hypothesized extinction vortex (Fagan & Holmes 2006). Models estimating extinction probabilities correctly include these potential accelerating threats resulting from small population size. The lesson from vaquitas is that these are indeed potential threats, but that their magnitudes may be altered as we measure the species' actual response to having a small population. Assuming all species will slip into the extinction vortex paints too grim a picture. Pronouncing a species doomed to extinction when the threat is human-induced is a self-fulfilling prophecy. Thus, conservation biologists need to account for more uncertainty about how small populations may respond to being small in their risk models, effectively communicate that uncertainty to managers and stakeholders, and continue to obtain data on the actual response of species to small population size to continually update the time left to save the species from extinction.

The other important result from the 2019 and 2021 research was the independent documentation that gillnet threats have not decreased for this species but have almost certainly increased in the past few years. As noted in Section 1, no gillnetting was observed during visual surveys for vaquitas in 2008, 2015, and 2017 during the opening months of the shrimp fishing season. In contrast, gillnetting for shrimp was seen within the ZTA at high levels in 2018, 2019, and 2021. Since totoaba fishing later in winter can be assumed to continue at high levels, the shrimp gillnets represent an increase in gillnets that would be encountered by vaquitas. It is important to remember that the loss of over half of vaquitas between 1997 and 2008 (Gerrodette et al. 2011) occurred when there was almost no totoaba gillnetting and the most valuable commercial fishery in the region was for shrimp, which also use gillnets known to kill vaquitas (D'Agrosa et al. 2000).

The recovery team (CIRVA) has many reports (available at https://iucn-csg.org) that consistently advise that the recovery of vaquitas is tied to developing vaquita-safe fishing methods and alternative livelihoods for the local fishing communities. Fishers using alternative fishing gears have never been observed during vaquita research. In 2021, no permits were issued for alternative gear in time for the shrimping season.

From our observations, it is clear that enforcement has not banished the illegal fishing that impacts conservation, research, and the social fabric of the local communities. This has recently been recognized by the Mexican government in a report to the Convention on International Trade in Endangered Species (CITES), in which it pointed out that it is necessary to seek new monitoring and control schemes (Gobierno de México 2021; https://cites.org/sites/default/files/eng/com/sc/74/S-SC74-28-05-A3.pdf). Certainly, there is a need to search for new enforcement schemes that include the participation of the local communities and all stakeholders. The simultaneous rapid transfer to vaquita-safe fishing methods with effective enforcement is key for vaquita recovery, which the research presented here supports is possible if vaquitas are guarded from illegal gillnetting within the small 12 × 24 km area where they remain.

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