Vaquita Bycatch in Mexico's Artisanal Gillnet Fisheries: Driving a Small Population to Extinction

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Abstract: *The world's most endangered marine cetacean, the vaquita (*Phocoena sinus*), continues to be caught in small-mesh gillnet fisheries throughout much of its range. We monitored fishing effort and incidental vaquita mortality in the upper Gulf of California, Mexico, from January 1993 to January 1995 to study the magnitude and causes of the incidental take. Of those factors studied, including net mesh size, soaktime, and geographic area, none contributed significantly to the incidental mortality rate of the vaquita, implying that the principal cause of mortality is fishing with gillnets* per se. *The total estimated incidental mortality caused by the fleet of El Golfo de Santa Clara was 39 vaquitas per year (95% CI = 14, 93), over 17% of the most recent estimate of population size. El Golfo de Santa Clara is one of three main ports that support gillnet fisheries throughout the range of the vaquita. Preliminary results indicate that fishing effort for San Felipe, Baja California, is comparable to that of El Golfo de Santa Clara, suggesting that this estimate of incidental mortality of vaquitas represents a minimum. We strongly recommend a complete and permanent ban on gillnets in the area. Alternative or supplemental mitigation strategies include (1) a maximum annual allowable mortality limit of vaquitas; (2) mandatory observer coverage of all boats fishing within the Upper Gulf of California and Colorado River Delta Biosphere Reserve; (3) extension of the Upper Gulf of California and Colorado River Delta Biosphere Reserve to encompass all known vaquita habitat; (4) rigorous enforcement of new and existing regulations; and (5) development of alternative sources of income for gillnet fishers.*

Captura Accidental de la Vaquita Marina en Redes Agalleras de Pesquerías Artesanales de México: Llevando una Población Pequeña hacia la Extinción

Resumen: *El cetáceo marino más amenazado del mundo, la vaquita marina (*Phocoena sinus*) sigue siendo capturado en redes agalleras de pesquerías de mallachica a lo largo de casi todo su rango de distribución. Para estudiar la magnitud y las causas de la captura incidental monitoreamos el esfuerzo pesquero y la mortalidad incidental de la vaquita en la parte superior del Golfo de California, México, desde enero de 1993 hasta enero de 1995. De los factores estudiados, incluyendo el tamaño de luz de malla, tiempo de inmersión y área geográfica, ninguno contribuyó significativamente a la captura incidental de la vaquita, lo cual implica que la causa principal de la mortalidad de la vaquita es la pesca con redes agalleras de por sí. La mortalidad incidental total estimada causada por la flota de El Golfo de Santa Clara, fue de 39 vaquitas al año (95% CI = 14, 93) más del 17% de la estimación más reciente del tamaño poblacional. El Golfo de Santa Clara es uno de los tres puertos principales que apoyan la pesquería con redes agalleras a lo largo del rango de distribución de la vaquita. Resultados preliminares indican que el esfuerzo pesquero de San Felipe, Baja California es comparable con el de El Golfo de Santa Clara, sugiriendo que esta estimación de mortalidad incidental de la vaquita es una estimación mínima. Recomendamos firmemente la prohibición completa y permanente de las redes agalleras en el área. Estrategias de mitigación alternativas o suplementarias incluyen: (1) un límite máximo anual permisible de mortalidad incidental de vaquitas; (2) cobertura obligatoria con observadores en todos lo botes de pesca dentro de la Reserva de la Biosfera alto Golfo de California y delta del Río Colo-*

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rado; (3) extensión de la Reserva de la Biosfera alto Golfo de California y del delta del Río Colorado para abarcar todos los hábitats conocidos de la vaquita; (4) ejecución rigurosa de las regulaciones nuevas y existentes; y (5) desarrollo de fuentes de ingreso alternativas a la pesquería con redes agalleras.

Introduction

One of the primary threats to biodiversity is the overexploitation of natural resources (Meffe et al. 1997). This is especially true of marine species, where overfishing and fisheries bycatch have serious effects on marine ecosystems (Dayton et al. 1995). The extinction of marine vertebrates is thought to be a rare and unlikely event (Casey & Myers 1998), but many species are severely threatened by directed or incidental harvesting (e.g., barndoor skate [*Raja laevis*], Casey & Myers 1998; coelacanth [*Latimeria chalumnae*], Hissman et al. 1998; several small cetaceans, Brownell et al. 1989).

The vaquita (*Phocoena sinus*), a small porpoise, is the most endangered marine cetacean; its range is limited to the upper Gulf of California, Mexico (Fig. 1; Gerrodette et al. 1995; Vidal 1995). The population size is small, with the most reliable and recent abundance estimate being 224 individuals (95% CI = 106, 470; Barlow et al. 1997). Although the life history of the vaquita is similar to that of its better-known congener, the harbor porpoise (*P. phocoena*; Hohn et al. 1996), the reproductive rate and thus the potential rate of increase for the vaquita population is thought to be lower than the 4% estimated for the harbor porpoise by Woodley and Read (1991). Rosel (1992) found no genetic variability in a mtDNA segment of 400 base pairs in a small sample of vaquita and attributed this to a possible population bottleneck. The high incidence of polydactyly in the vaquita also suggests inbreeding (Torre 1995).

Documented mortality of the vaquita in gillnet fishery operations has been occurring at least since the 1950s (D'Agrosa 1995), possibly since the 1930s (Vidal 1995), and now threatens its survival. Since first described in 1958 (Norris & McFarland 1958), the vaquita has been listed as an endangered species by several national and international agencies and organizations (World Conservation Union 1978; U.S. Endangered Species Act 1985; Klinowska 1991; Diario Oficial de la Federación [DOF] 1994). It has long been thought that gillnets, which are used widely in the upper Gulf of California, are the biggest threat to the vaquita (Vidal 1995). Large-mesh gillnets (>20 cm), particularly those set for a sciaenid fish called totoaba (*Totoaba macdonaldi*, also endemic to the region and endangered by overfishing) were thought to be the primary cause of unsustainable rates of incidental mortality, at least during the 1980s and early 1990s. Between 1985 and 1992, at least 35 vaquitas were taken each year in gillnets set for totoaba, several shark species, and sierra and mackerel (*Scomberomorus* spp.) (Vidal 1995).

Through the years there have been many attempts to manage and protect the natural resources of this region. In spite of regulations banning the totoaba fishery and the use of large-mesh gillnets (DOF 1955, 1975, 1992, 1993, 1994), this fishery continued, and others using smaller-mesh (<20 cm) gillnets emerged or expanded. In 1993–1994, these small-mesh gillnets were also shown to catch vaquitas, adding to growing concern for the survival of the species (D'Agrosa et al. 1995). In June 1993, the Mexican government established the upper Gulf of California and Colorado River Delta Biosphere Reserve (DOF 1993), principally to protect vaquita and totoaba and their habitat (DOF 1993, 1994).

We present the first estimates of fishing effort and incidental vaquita mortality caused by small-mesh gillnet fisheries from El Golfo de Santa Clara, Sonora, and an analysis of factors that may contribute to this mortality. In addition, we provide a description of concurrent fishing activities at other ports within the vaquita's range to illustrate the potential effect of gillnet fisheries throughout the upper Gulf.

Methods

Data Collection and Analysis

We monitored the artisanal gillnet fishing activities in the upper Gulf of California periodically between 23 January 1993 and 25 January 1995. In El Golfo de Santa Clara, we monitored the fishing activity of 235 pangas (small outboard-motor boats) continuously from 23 January to 7 August 1993 (except for 7 days between 7 and 14 May) and intermittently (11 1- to 6-day visits) from 15 September 1993 to 24 April 1994. To collect data on fishing effort and incidental mortality of the vaquita, we interviewed the greatest number of fishers possible on the beach when they returned from fishing. In addition, to corroborate the data provided by the fishers, we placed one observer per fishing day on the first panga that agreed to take the observer, for a total of 54 sam-

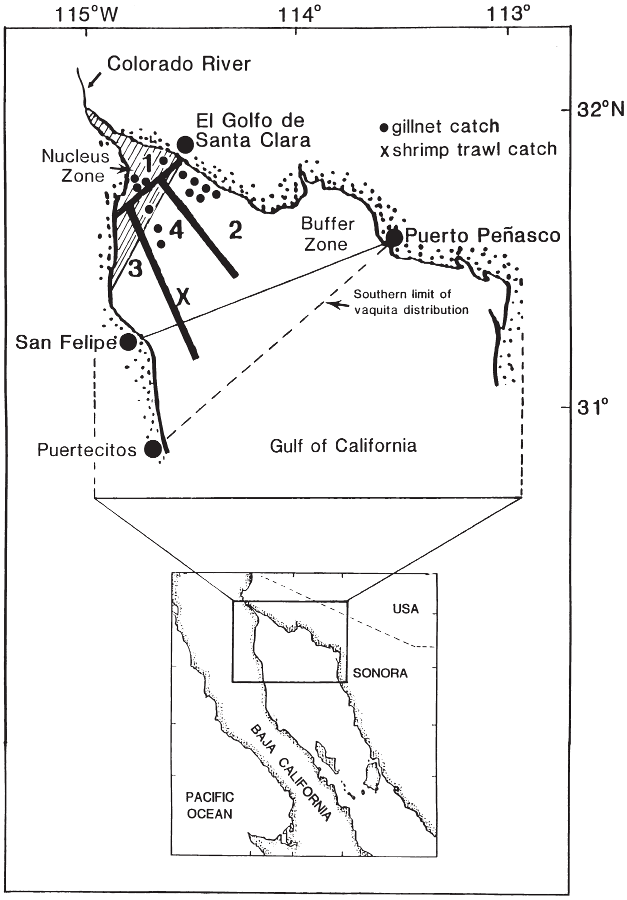

Figure 1. Study area denoting the boundaries of the upper Gulf of California and Colorado River Delta Biosphere Reserve, locations of incidental capture of vaquitas during 1993–1994, and four zones within which fishing effort occurs: (1) Colorado River Delta, from El Machorro, Sonora (lat 31°40′N, long 114°30′W) across the Gulf to El Moreno, Baja California (approximately lat 31°12′N, long 114°50′W); (2) coast of Sonora, from El Machorro south to El Borrascoso (lat 31°29′N, long 114°02′W) and west to central area of the Gulf; (3) coast of Baja California, from El Moreno to San Felipe and east to Rocas Consag; and (4) central region, which roughly follows one of the main river channels.

pled pangas (for details see D'Agrosa et al. 1995). Between 26 January 1993 and 25 January 1994, we recorded 2921 fishing trips; it was not possible to interview all fishers, however, so we sampled a total of 1113 fishing trips, 1066 (96%) through interviews and 47 (4%) through observers aboard pangas. Between January 1994 and April 1994, we recorded an additional 236 fishing trips, of which we sampled 102. Between January 1993 and January 1994, 14 vaquitas died in gillnets with mesh sizes ranging from 7 to 15 cm (D'Agrosa et al. 1995); three of these deaths could not be used for analysis because the fishery associated with these mortalities was not known. There were no observed (or reported) mortalities between February and April 1994.

In addition, we conducted five concurrent visits (28 days total) to El Golfo de Santa Clara and Puerto Peñasco, Sonora, and San Felipe, Baja California, between 18 October 1994 and 25 January 1995. During this period we recorded 739 trips in El Golfo de Santa Clara, 1046 trips in San Felipe, and 237 trips in Puerto Peñasco, of which we sampled 351, 314, and 190 trips, respectively. The number of pangas capable of fishing gillnets varied between ports during this period, with 250 in El Golfo de Santa Clara and 250 in San Felipe, but only 80 in Puerto Peñasco. No data were collected on fishing activities in Puertecitos, Baja California, or in the nearby fishing camps.

Factors Influencing Mortality Rates

Identification of factors that may affect mortality rates is essential to the design and implementation of management strategies to reduce the incidental take of vaquita. To address this issue, we investigated the effects of geographic area, mesh size, net deployment time, soaktime (difference between time of net set and time of net haul), and fishery type on mortality per net using data from January 1993 to April 1994. The number of sets per net was not consistently available for the entire study period, so we used mortality per net instead of mortality per set. Data for 1620 nets were used in this analysis. We determined the levels of each of the factors by probable as well as existing management guidelines or by the ranges of the various variables representing the factors. We divided the upper Gulf into four zones (Fig. 1): (1) Colorado River Delta; (2) coast of Sonora; (3) coast of Baja California; and (4) central Gulf region. We grouped mesh sizes into <10 cm and ≥ 10 cm, net deployment time into before and after 1400 hours, and soaktime into short (0–15 hours) or long (>15 hours) duration. We grouped the five gillnet fisheries into two categories: surface fisheries (sierra and mackerel) and subsurface fisheries (shrimp [*Penaeus stylirostris*, *P. californiensis*], chano [*Micropogonias megalops*], corvinas [*Cynoscion* spp.], and several species of sharks and rays).

To test for the effects of these factors on vaquita mortality per net, we used the framework of a generalized linear model (McCullagh & Nelder 1989; Chambers & Hastie 1992), assuming a binomial distribution for the number of nets in which a vaquita death occurred. That is, we assumed a binary distribution for mortality per net in individual nets. A binary distribution is plausible because there were no nets (or trips), recorded from observation or interview, with more than one vaquita death. We assumed a linear logistic model (Collett 1991) for the dependence of mortality per net on the factors described above and selected influential factors by a stepwise fitting procedure.

Fishing Effort

We measured fishing effort as the number of pangas fishing per day. Direct observations of fishing activities in El Golfo de Santa Clara suggested that each panga made one trip per day, so the number of fishing trips per day equals the number of pangas fishing per day. We did not use other measures of effort, such as number of nets, number of net sets, or soaktime, because the data for these variables was not consistently available throughout the study period. Whenever possible, the observers recorded direct counts of the number of pangas fishing on a given day. When direct counts were not possible, the fishers provided an estimate of the number of pangas fishing from daily counts of the number of active pangas at each fishing ground. Because counts provided by fishers for the same fishing ground differed, we estimated the number of pangas fishing per day by first computing the average number of pangas fishing at each fishing ground and then summing these averages over all locations. We treated these estimated counts as direct counts.

We explored the relationship between the number of pangas fishing and day of the week, tidal amplitude, and type of fishery to estimate the fishing effort of the fleet of El Golfo de Santa Clara on days that were not monitored. The number of pangas that fished on a given day varied with the day of the week, with almost no fishing occurring on Sundays (Fig. 2). We grouped the days of the week into three categories: (1) Sunday; (2) Friday, Saturday, and Monday; and (3) Tuesday, Wednesday, and Thursday. Most of the fisheries used driftnets, so fishers did not fish during neap tides (Fig. 2) because catches were low. Tides in this area are mixed semidiurnal (Castro & Huber 1992), so we used the amplitude between the first maximum and the first minimum in all of the analyses. Tidal amplitude data were obtained from the Instituto de Geofísica (1993, 1994). We grouped tidal amplitudes into three categories: (1) low, <3 m; (2) medium, ≥ 3 and <5 m; and (3) high, ≥ 5 m. Effort was highly variable between fisheries because the duration of fishing seasons and the number of active fishers in each season were not constant (Fig. 2). We grouped fisheries into three categories: (1) chano; (2) shark, ray, and corvina; and (3) shrimp and sierra. Other factors that may affect the distribution of fishing effort, such as the previous day's catch, weather, availability of fuel, local festivities, or socioeconomic conditions (e.g., availability of household money) could not be included in this analysis because data were not available for the entire study period or because data were not collected.

To determine the relationship between the number of pangas that fished on a given day and the tides, day of the week, and fishery, we analyzed the data within the framework of a generalized linear model, assuming a log-linear model (McCullagh & Nelder 1989) for the mean number of pangas fishing on a given day (μ). That is, we assumed that

$$\ln(\mu) = \text{global constant} + \text{fishery effect} + \text{day effect} + \text{tidal amplitude effect},$$

where ln denotes natural logarithm. We used iteratively reweighted least squares (Chambers & Hastie 1992) to estimate the coefficients for a parameterization of this model. From the parameterized model we predicted the mean number of pangas fishing on a given day for days that were not monitored. We estimated the total number of fishing trips made by the fleet of El Golfo de Santa Clara between 26 January 1993 and 25 January 1994 by summing the fishing trips for those days that were monitored plus the estimated numbers of trips for unmonitored days. We estimated the variance of the total number of fishing trips by the delta method (Rice 1988).

To obtain an idea of the magnitude of fishing activities throughout the upper Gulf, we compared daily fishing

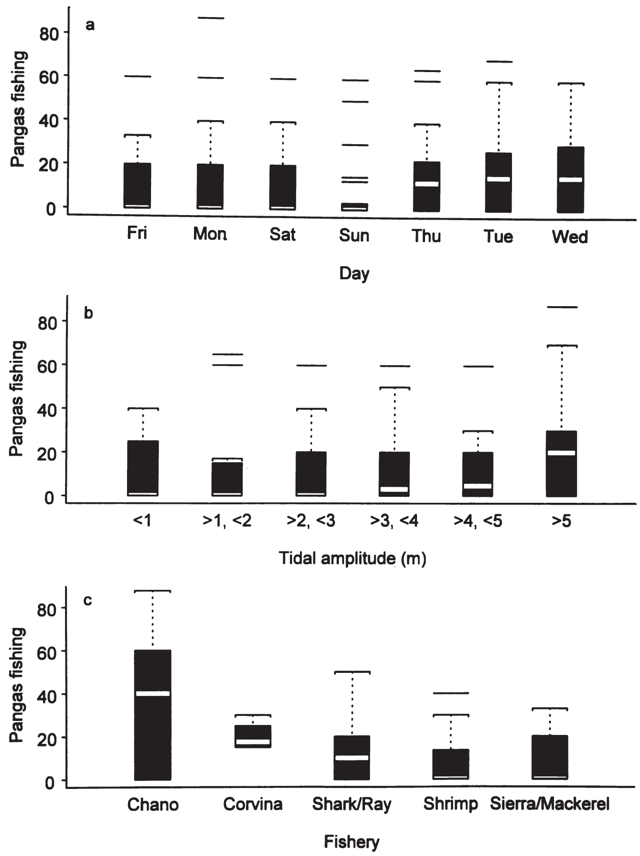

Figure 2. Distribution of number of pangas fishing per day between January 1993 and January 1994 in relation to (a) day of week, (b) amplitude between tides, and (c) fishery. Solid rectangles encompass middle 50% of data; white line is median; solid unconnected lines are extreme values; solid lines connected with dashed line represent 97% of data.

effort among ports for the shrimp fishery (the only gillnet fishery active in El Golfo de Santa Clara between October 1994 and January 1995), assuming a linear relationship for effort among ports. The slope of this linear relationship was estimated by least squares.

Incidental Mortality

We computed the average mortality rate per trip as the number of reported mortalities in sampled trips, divided by the number of sampled trips. We estimated the variance of mortality per trip according to the formula for the variance of a proportion, assuming a binary distribution for mortality per trip in individual trips (Collett 1991). We calculated mortality rates separately for data obtained from interviews and for data obtained by onboard observers and then compared these two mortality rates to detect significant differences at the 5% level, assuming an approximately Gaussian distribution for the difference in mortality rates (Collett 1991, equation 2.14).

We estimated the total mortality of the vaquita from 26 January 1993 to 25 January 1994 for El Golfo de Santa Clara as the product of total estimated fishing effort and mortality per trip. We calculated an estimate of the variance of total mortality according to Goodman (1960), assuming that mortality per trip and total estimated fishing effort were uncorrelated. From the Tchebysheff theorem (Mann 1992), we calculated approximate 95% confidence intervals for total mortality.

Results

Factors Influencing Mortality Rates

We found no significant dependence of the logarithm of the odds ratio for mortality per net (Table 1) on any of the factors or combination of factors investigated. The changes in deviance—a measure of the explanatory power of a factor—were not significant at the 10% level for any of the factors considered, and most p values were >0.30. We also analyzed fisheries as such (i.e., shrimp, chano, corvinas, sharks, sierra and mackerel, and rays) to determine if there was any dependence of the logarithm of the odds ratio for mortality per net on the type of fishery. The model was also not significant ($p = 0.86$).

Fishing Effort

We estimate that fishers of El Golfo de Santa Clara conducted 3946 trips (SE = 139) between 26 January 1993 and 25 January 1994 (Fig. 3). The mean number of pangas fishing per day depended significantly on the type of fishery ($p < 0.01$), day of the week ($p < 0.01$), and tidal amplitude ($p < 0.01$) (Table 2). Thus, we consider this estimate an improvement over an estimate based on the overall mean (4936 pangas). Nonetheless, departures of data from the model were evident. Other single-distribution models that accommodate greater variability than the Poisson (e.g., the negative binomial) did not significantly improve the fit. Estimates based on a Poisson model with first-order interactions (3905 pangas) and on a stratified ratio estimator (3991 pangas) were similar. The lack of fit is most likely caused by factors, such as weather and local holidays, that were not adequately described by a day effect and that could not be included in our model because of lack of data, underscoring the need for future studies to take the steps necessary to ensure continuous monitoring of fishing effort.

Gillnet fishing activities were variable among ports during the "shrimp season" in late 1994. For example, between October 1994 and January 1995 only the shrimp fishery (7-cm mesh gillnets; D'Agrosa et al. 1995) was operating in El Golfo de Santa Clara. Shrimps were also fished with 7-cm mesh gillnets in San Felipe from early September to at least 1 December, but then sierra and mackerel were fished with 7.6-cm mesh gillnets, and in January baqueta (possibly *Epinephelus acanthistius*) were fished with longlines. In Puerto Peñasco, approximately 20 pangas fished for shrimps with 7-cm

Table 1. Order of stepwise selection of factors from the linear logistic model for vaquita mortality per net.

Factor[a]	*Change in deviance*[b]	*Degrees of freedom*	p[c]
Mesh size	0.87	1	0.35
Mesh size + area	2.15	3	0.54
Mesh size + area + time of net deployment	0.46	1	0.50
Mesh size + area + time of net deployment + fishery	1.71	1	0.19
Mesh size + area + time of net deployment + fishery + soak time	0.01	1	0.93

[a] *At each step, the factor with the smallest* p *value was added to the model, even if the factor was not significant.*
[b] *Change in deviance represents the difference in residual deviances of models with and without the additional factor. Deviance for the model with only a global constant (null model) = 131.76.*
[c] *Approximate* p *values were obtained by assuming that the change in deviance follows a chi-square distribution with the appropriate degrees of freedom.*

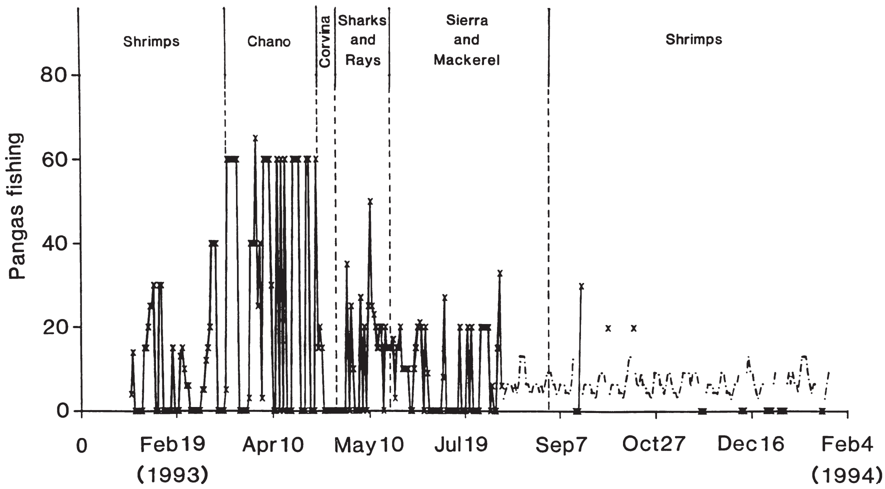

Figure 3. Observed fishing effort (x; observations are connected by a solid line to indicate continuous monitoring) and estimated fishing effort (dotted line) between January 1993 and January 1994. Fisheries indicated in upper region of the graph.

mesh gillnets, principally in the same areas used by El Golfo de Santa Clara fishers. During the same period, however, several pangas bought seafood from commercial shrimp boats, others took divers to get bivalves, and still others fished baqueta with longlines.

Observed fishing effort for the shrimp fishery in El Golfo de Santa Clara from October 1994 to January 1995 was significantly correlated with that for San Felipe, but not with that for Puerto Peñasco. Fishing effort for the shrimp fishery in San Felipe was more than 1.5 times that in El Golfo de Santa Clara (t = 8.20, df = 15, $p <$ 0.01). No significant linear relationship was found between fishing effort for the shrimp fishery of Puerto Peñasco and that of El Golfo de Santa Clara (t = 0.16, df = 12, $p >$ 0.20), suggesting that these two ports did not allocate effort for shrimp fishing in a similar manner.

Table 2. Estimated coefficients for the log-linear model of mean number of pangas fishing per day in El Golfo de Santa Clara, Sonora, Mexico.

Factor[a]	*Estimated coefficient*	*Standard error*	t	p[b]
Global constant[c]	2.53	0.293	8.63	<0.01
Shk-cor[d]	−0.98	0.200	−4.93	<0.01
Shr-sie	−1.47	0.166	−8.85	<0.01
FSM[e]	0.45	0.275	1.65	0.10
TWR	0.81	0.271	2.99	<0.01
MED[f]	0.36	0.183	1.99	0.05
HIGH	0.71	0.199	3.57	<0.01

[a] *Shk-cor, shark and corvina fisheries; shr-sie, shrimp and sierra and mackerel fisheries; FSM, Friday, Saturday, and Monday; TWR, Tuesday, Wednesday, and Thursday; MED, medium tidal amplitude; HIGH, high tidal amplitude.*
[b] *The* p *values are for a two-tailed test based on Student's* t *distribution with 224 degrees of freedom (*t *values have been scaled by an estimate of the dispersion parameter). The overall reduction in deviance attributable to the model was 1843 (6 df,* p < 0.01*).*
[c] *Global constant represents the chano fishery on Sundays at low tidal amplitude.*
[d] *Change in deviance (with respect to full model) associated with the fishery effect was 1360, 2 df; approximate* F *= 37.0; 2, 224 df.*
[e] *Change in deviance (with respect to full model) associated with the day of the week effect was 201, 2 df; approximate* F *= 5.5; 2, 224 df.*
[f] *Change in deviance (with respect to full model) associated with the tidal amplitude effect was 210, 2 df; approximate* F *= 5.7; 2, 224 df.*

Incidental Mortality

We estimate that one animal in 50 trips (observer data) to one animal in 100 trips (observer plus interview data) was taken between 26 January 1993 and 25 January 1994 (Table 3). There was no significant difference between the average mortality rate based on observer data and that based on interview data (z = 0.81, p = 0.42). For comparison, we computed estimates of mortality per trip for both the observer data and the pooled data (observer plus interviews) (Table 3). We computed unstratified estimates of mortality rates because none of the factors investigated contributed significantly to the mortality rate of the vaquita (Table 1; D'Agrosa 1995).

The total estimated incidental vaquita mortality from fishing activities of El Golfo de Santa Clara between 26 January 1993 and 25 January 1994 was 39 vaquitas (se = 12) when the pooled data were used (95% CI = 14, 93) and 84 vaquitas (SE = 83) when only the data collected by observers were used (95% CI = 14, 455) (Table 3). Neither of these incidental mortality estimates includes all of the fishing activities in the upper Gulf (i.e., other fishing ports, fishing camps, and gears). Although we have no data on mortality for other ports, the occurrence of fishing effort in other ports and nearby fishing camps suggests that the actual annual mortality of the vaquita may be higher. Given that the number of pangas in El Golfo de Santa Clara and in San Felipe has changed little between 1990 (approximately 226 and 260, respectively; Vidal 1995) and 1995 (250 in each port), and assuming that fishing activities in San Felipe were similar to those in El Golfo de Santa Clara, the number of trips made by pangas in San Felipe may have been compara-

Table 3. Mortality rates per trip (mpt) and total estimated number of vaquita mortalities (M) for El Golfo de Santa Clara, Sonora, Mexico, 26 January 1993 through 25 January 1994.[a]

Data[a]	*Deaths*	*Trips*	*mpt*	*SE*	*M*	*SE*	*CI*[b]
All	11	1113	0.0099	0.00297	39	12	14, 93
Observer	1	47	0.0213	0.02104	84	83	14, 455

[a] *All, interview plus observer data; observer, observer data only.*
[b] *Approximate 95% confidence intervals for M.*

ble to that of pangas of El Golfo de Santa Clara. No data were available for Puerto Peñasco. Thus, several mortality estimates can be calculated from these results (Table 4), ranging from 14 (observed mortalities) to 168 (estimate for El Golfo de Santa Clara and San Felipe based on observer data). We consider the estimate of 39 vaquitas per year to be the most reasonable because it is based on the largest sample size but does not involve extrapolation to fishing ports for which no mortality-rate data were available.

Discussion

We have used estimates of mortality per trip and total number of trips to compute an estimate of total annual incidental mortality of the vaquita in El Golfo de Santa Clara, one of three main ports that support gillnet fisheries throughout the range of the vaquita. Preliminary results indicate that fishing effort for San Felipe, Baja California, is comparable to that of El Golfo de Santa Clara, suggesting that our estimate of 39 (95% CI = 14, 93) vaquita mortalities per year represents a minimum. No significant dependence of vaquita mortality per net on area, mesh size, net deployment time, fishery type, or soaktime was found, most likely because the number of documented deaths (11) was small in relation to the number of monitored nets (1620).

Results of a power analysis for individual factors, based on the assumption that the linear logistic model is correct, suggest that our analysis of the by-net data had low power (Taylor & Gerrodette 1993). For example, given our sample size and assuming an alpha level (α) of 0.20, we estimated that the true difference in mortality per net between the two levels of mesh size would have to have been almost three times that actually observed to have been detectable with a probability of 0.76 and almost six times that actually observed to have been detectable with a probability >0.90. On the other hand, given the observed difference in mortality per net for the two mesh-size categories, we estimated that 3 more years of data (at the same level of sampling coverage) would be necessary to have a 71% chance of detecting a true difference of the magnitude actually observed ($\alpha = 0.20$). We estimated that statistical power was similar for the other factors. Given the most recent abundance and mortality estimates, delaying drastic conservation measures to wait for several more years of data to be collected could put the vaquita at great risk. Thus, if we take a precautionary approach, our results suggest that the principal cause of the incidental mortality of the vaquita is fishing with gillnets per se.

The high levels of incidental mortality of vaquitas may indicate that the population is larger than calculated by Barlow et al. (1997). Even bycatch of vaquitas at the level of the observed mortalities (14) is unsustainable, with an annual mortality rate of 6.25% of the estimated population size of 224 (Barlow et al. 1997). With the exception of several surveys by Silber (1988, 1990) and Gerrodette et al. (1995), there has been no search effort in the extreme northwest of the upper Gulf of California because most vessels used in the surveys could not enter the shallower channels (<20 m). Sightings by Sánchez-Navarro and Robles (Table 5) and captures documented by Vidal (1995) and D'Agrosa et al. (1995) indicate that vaquita inhabit these shallow waters. To sustain the current estimated mortality of 39 vaquitas per year, assuming an optimistic potential rate of increase of 4%, the vaquita population would have to be at least 975 animals, a figure more than twice the upper boundary of the abundance estimate by Barlow et al. (1997).

One must consider more than just the small population size and low potential rate of increase when exam-

Table 4. Estimates of total annual mortalities of vaquita, calculated with different mortality rates, and the corresponding percentage of the estimated population size of 224 (Barlow et al. 1997).

Data used[a]	*Mortality*	*Population (%)*
Observed mortality		
EGSC	14	6.25
Calculated mortalities		
EGSC all data	39	17.41
EGSC observer data only	84	37.50
EGSC + SF[b] all data	~78	~34.82
EGSC + SF observer data only	~168	~75.00

[a] *EGSC, El Golfo de Santa Clara, Sonora; SF, San Felipe, Baja California.*
[b] *We have assumed, based on the number of boats fishing, that the SF pangas conducted the same number of trips between January 1993 and January 1994 as the pangas in EGSC. Thus, the total estimated incidental mortality for both EGSC and SF is twice the estimate for EGSC.*

Table 5. Vaquita sightings during *Ambar y Lobo* cruise, 20–30 April 1993*.

Day (April 1993)	*Hour sighted*	*Latitude (N)*	*Longitude (W)*	*Depth (m)*	*Individuals*
21	10:00	31:10.25	114:39.43	15.2	1
21	11:37	31:10.58	114:35.98	18.3	1
21	13:30	31:10.58	114:35.98	10.6	2/1
21	14:30	31:10.60	114:36.45	15.2	4
22	16:00	31:06.26	114:44.95	15.2	1
25	07:21	31:06.51	114:42.03	15.2	2
25	13:35	31:14.69	114:42.33	15.2	1
25	13:55	31:14.00	114:42.00	15.2	3
27	11:10	31:02.28	114:44.02	15.2	2/1
28	13:10	31:11.65	114:39.34	18.3	2
28	16:20	31:06.62	114:40.25	15.2	3/1

**Hour sighted, time begin sighting; depth, water depth; individuals, number of individuals. Unpublished data used with permission of M. Sánchez Navarro of México Desconocido and A. Robles of Conservation International.*

ining the effect of incidental mortality on this population. Low genetic variability (Rosel 1992) could reduce the population's ability to withstand natural environmental changes. Furthermore, the bimodal age structure (Hohn et al. 1996) could reflect either spatial-temporal segregation of the vaquita or the extermination of juvenile vaquitas due to high fishery-related mortality levels in the past. This, in conjunction with other negative pressures, such as habitat degradation, possible competition with fishers for food sources, and incidental mortality in gillnets, could precipitate the species' extinction even if the population is much larger than estimated currently. We conclude that fishery-related mortality needs to cease immediately.

Management in the Upper Gulf of California

Mexico has taken steps to avoid many of the problems of traditional reserves by embracing the biosphere reserve concept and creating the Upper Gulf of California and Colorado River Delta Biosphere Reserve (Instituto Nacional de Ecología 1995). The management plan for the reserve was created to reduce threats to the vaquita, to protect the ecosystem, and to ensure sustainable development for its residents (Instituto Nacional de Ecología 1995). The reserve has two main areas: the nucleus zone and the buffer zone (Fig. 1). All fishing within the nucleus zone is prohibited. Controlled fishing is permitted in the buffer zone. Although the management plan acknowledges that the most significant threat to the vaquita population is the use of gillnets within the reserve, it fails to include any specific measures to reduce vaquita mortality in gillnets.

Based on our analysis, we believe the best solution for the vaquita would be an immediate ban on the use of all gillnets within vaquita habitat and provision of an alternate source of income for local residents. Currently the vaquita remains vulnerable to fishing activities over more than half of its known range; approximately 40% of vaquita sightings made in August 1993 occurred south of the buffer zone (Gerrodette et al. 1995). Such a gillnet ban would require that the reserve be extended to include the southern portion of the vaquita's range (Fig. 1) and that the ban on all gillnet fishing activity be extended from the nucleus zone to cover the entire reserve. Because we were unable to detect a significant fishery effect (albeit at low statistical power), and because vaquitas were taken in four of the five fisheries at levels that exceed their estimated maximum potential rate of increase (Table 6), the ban should be applied to all gillnet fisheries.

Alternative protection for the vaquita should be provided by establishing (1) a maximum allowable annual incidental mortality and (2) a mandatory 100% observer coverage program. An annual mortality limit of vaquitas could be based on the concept of potential biological removal (PBR) used in the U.S. Marine Mammal Protection Act (MMPA; Wade 1998). Under the MMPA, PBR is calculated as the product of a minimum population estimate (N_{min}), one-half of the maximum net productivity rate (R_{max}) and a recovery factor (F_r). Assuming that N_{min} = 106 (Barlow et al. 1997), R_{max} = 4% (Hohn et al. 1996), and F_r = 0.1 (minimum recovery factor), PBR for vaquita is 0.212/year. Alternatively, the derivation of PBR used in the Declaration of Panama (0.1% of N_{min}; International Dolphin Conservation Program Act 1997) could be used, especially because Mexico has recently adopted such a management scheme regarding the tuna-dolphin issue (National Research Council 1992; Hall 1998). Using either definition of PBR, at most one vaquita mortality would be allowed before the fisheries closed for the rest of the year. In fact, observed vaquita mortality exceeds PBR for four of the five gillnet fisheries (Table 6). Under the PBR strategy, if the vaquita population increases, so would N_{min} and the maximum allowable mortality limit.

To guarantee compliance with any mortality limit, complete observer coverage should be mandatory for all boats that fish with gillnets within the reserve. For this monitoring program to be effective, the southern limit of the biosphere reserve needs to be extended to include Puertecitos, Baja California, to protect the vaquita population throughout its entire known range. Moreover, it may not be enough to monitor just the gillnet fisheries of the upper Gulf. Other fisheries within the reserve, such as the shrimp and chano trawl fisheries, are also known to take vaquitas (D'Agrosa et al. 1995; Vidal 1995). Thus, to ensure complete coverage of fisheries affecting the vaquita, trawl fisheries should be included in any monitoring program. In addition to monitoring bycatch of vaquita and other species, the observers would help fulfill the reserve's mandate of continuing scientific investigation (Instituto Nacional de Ecología 1995) by collecting data on the vaquita and other marine mam-

Table 6. Observed and estimated fishing effort and mortalities of vaquita by fishery[a] for El Golfo de Santa Clara, Sonora, 26 January 1993 through 25 January 1994.

Fishery	Recorded trips	Estimated trips	Observed mortality	Sampled trips[b]	Mortality rates[c] all	Mortality rates[c] observer	Estimated mortality[c] all	Estimated mortality[c] observer
Shrimp	525	1358	3	304	0.0099	0	13	0
Chano	1486	1486	4	358	0.0112	0.0556	17	83
Corvina	50	50	0	7	0	0	0	0
Sharks and rays	470	470	3	215	0.0154	0	7	0
Sierra and mackerel	390	582	1	259	0.0039	0	2	0

[a]*Fishing effort stratified by fishery (trips/fishery/day;* n *= 1143 trips) is larger than the number of observed trips (trips/day;* n *= 1113 trips) because during transitions from one fishery to the next some pangas conducted two different fishing activities in one trip.*
[b]*Used in the estimation of mortality rates.*
[c]*All, interview plus observer data; observer, observer data only; mortality rates, observed mortality per sampled trips; estimated mortality, mortality rate × estimated trips.*

mals, fishes, migratory and resident birds, and the environment.

The enforcement of regulations in reserves and the establishment of alternative sources of income for local residents are crucial to the survival of the species being protected. Poaching within reserves due to limited resources and personnel dedicated to enforcement has further reduced many endangered populations (e.g., the Sumatran rhino [*Dicerorhinus sumatrensis harrisoni*; Rabinowitz 1995] and black rhino [*Diceros bicornis*; Rachlow & Berger 1997]). In Mexico, even though the totoaba fishery was banned in 1975 (DOF 1975), an estimated 70 tons were taken per year until 1992 (Vidal 1995). In addition, gillnet fisheries in the upper Gulf play a key role in the local economy because of the remote location and the harsh terrestrial environment. Thus, creating infrastructure such as fish storage and processing plants to support and improve alternate fishing techniques that are less dangerous to the vaquita (e.g., longlines for fishing sharks and rays) are essential to the success of the reserve. Although these are arguably the most difficult and expensive elements of natural resource conservation, adequate enforcement, especially when it involves public participation, and the development of economically feasible alternative sources of income, can lead to the successful protection of a species (e.g., Hector's dolphins [*Cephalorhynchus hectorii*; Dawson & Slooten 1993], and reef fishes [Roberts 1995]).

Can the Vaquita Be Saved?

Due to its low abundance, limited distribution, low reproductive potential, and limited genetic variability, the vaquita may be a classic example of a relict population vulnerable to fishing pressure and its effects on the environment (Vincent & Hall 1996). The simple fact that the observed mortality for just one port within its habitat range exceeds the maximum estimated potential rate of increase is a clear indication that drastic actions must be taken immediately to avoid the extinction of this rare species. In 1997 Mexico created the International Committee for the Recovery of the Vaquita (Comité Internacional para la Recuperación de la Vaquita, CIRVA) with the specific aim of creating a recovery plan for the vaquita. By considering measures that emphasize the greatest likelihood of recovery based on current knowledge of the species, CIRVA is mandated to create a step-by-step manual for present and future agencies in charge of the recovery of this species. After their first meeting in early 1997, CIRVA concluded that mortality in gillnets was the most important short-term risk factor and that immediate action should be taken to reduce such mortality. New abundance estimates and a quantitative description of the species' critical habitat are underway. At their second meeting in early 1999, CIRVA drafted a three-phase series of recommendations for the immediate protection of the vaquita (L. Rojas-Bracho, personal communication). If CIRVA is successful, not only will the vaquita have a chance to survive, but the recovery plan could provide a framework for using refugia to save other small, endangered populations around the world.

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