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Analysis of the artisanal fisheries of San Felipe, Mexico: Estimating incidental mortality of the vaquita (*Phocoena sinus*)

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Abstract

The vaquita (*Phocoena sinus*) is the most critically endangered cetacean species in the world and is a small porpoise endemic to the northern Gulf of California, Mexico. As fishing efforts increased greatly, over half of the species population was lost in 11 years. Gillnets for shrimp cause very high rates of by-catch, thus incidental mortality is the principal threat for vaquita survival. We estimated the current fishing effort in the Upper Gulf of California in order to estimate vaquita by-catch mortality. Fishing activities carried out by artisanal fishermen in the Port of San Felipe were monitored from September 15 - December 14, 2013 and from October 17 - October 21, 2013 in El Golfo de Santa Clara. Information on the number of pangas fishing was collected daily. Since every boat goes out and back once per day, we consider the number of trips as our measure of fishing effort. A total of 5,505 trips were observed during the sample period. Using Bayesian analysis, we estimated the fishing effort for the days that were not monitored to cover the entire shrimp season. A total of 50,692 trips were estimated using the Markov Chain Monte Carlo. We estimated the mortality rate per trip using the fishing effort estimation and available demographic information of the vaquita population. The mortality rate of the vaquita resulted in $3.15\text{x}10^{-6}$ trips^{-1}. By 2014, the estimate of current vaquita abundance was 97 individuals and using the number of fishing trips estimated per day, we estimated 28 vaquitas caught in artisanal nets for the 2013-2014 period. With this amount of fishing effort and lack of enforcement, unless drastic action is taken, the vaquita will be lost. [JMATE. 2015;8(1):26-35]

Keywords: *Phocoena sinus*, fishing effort, incidental mortality

Introduction

The vaquita (*Phocoena sinus*), a small porpoise endemic to the northern Gulf of California, is the most critically endangered cetacean species in the world. Their most concentrated distribution area is about 2,235 km^2, approximately 40 km east of San Felipe in Baja California, Mexico (26). Due to its capture in gillnets in a remote region where fishing has long been a primary economic activity, which provides the sole source of income for many people, this makes the vaquita uniquely vulnerable. As fishing efforts increased greatly in the past decades, over half of the species population was lost in 11 years, with only about 245 (95% C.I. 68–884) porpoises remaining in 2008 (13). The Vaquita Refuge protects only about half of the population and illegal gillnet fishing is still common inside and outside the Refuge. Gillnets for fish and shrimp cause very high rates of by-catch of vaquitas, thus incidental mortality in gillnet fisheries has been recognized as the principal threat for the vaquita (9, 18, 25-27).

In 1993, D'Agrosa *et al*. conducted the first and only study of vaquita by-catch (9). The study monitored the artisanal fisheries of El Golfo de Santa Clara through on-board observations and interviews with local fishermen as they returned from fishing. The by-catch mortality of the vaquitas was estimated to be 39 vaquitas per year (95% I.C. 14-93) in the El Golfo de Santa Clara. Assuming that in 1993 the artisanal fleet of San Felipe and the one in El Golfo de Santa Clara had the same fleet size, the incidental mortality of the vaquita population resulted in about 78 individuals for the upper Gulf of California (9, 26).

The estimations by D'Agrosa *et al*. have been used to estimate the abundance and the status of the vaquita population ever since (12, 16, 17). However, there is some uncertainty on the estimation of the vaquita by-catch due to the assumption that the fleet size was the same for both locations, the sampling period was not conducted during the most productive months of the shrimp season (October to December), and the artisanal shrimp fishery was going through an anomalous year during the study period (8, 26). All of these factors could have resulted in a subestimation of the fishing effort. On the other hand, the model used by D'Agrosa *et al*. could have been biased, because there was no monitoring of the shrimp fishery from

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September to December, probably resulting in an overestimation of incidental mortality.

In this paper we provide an updated estimation of the fishing efforts of the artisanal fleets of San Felipe and El Golfo de Santa Clara during shrimp fishing season in the upper Gulf of California (September to March) in order to improve vaquita by-catch mortality models to estimate population numbers and its trend and also provide further information on active number of artisanal boats in the upper Gulf of California. These two elements have been requested by the Mexican Ministry of Environment (SEMARNAT) in order to contribute to vaquita conservation actions.

Methods

Fishing activities carried out by artisanal fishermen in the Port of San Felipe (SF), Baja California, Mexico, were monitored from September 15th to December 14th 2013, covering the most productive months of the shrimp season (8). Information on the number of artisanal fishing boats or pangas leaving and returning to port was collected daily through direct observations using Fujinon 7X50 binoculars. In the morning, the number of pangas was documented from 4:30 to 7:30. In the evening, pangas were counted from 16:00 to 19:00 from the San Felipe Lighthouse using Big Eye 20x120 binoculars. This elevated location allowed to cover a more representative portion of the sites where fishermen go out to sea. Other than the number of pangas leaving and returning to shore, information was also collected on number of fishermen and nets per boat, outboard engine size, boat condition, and direction of navigation (as an index of apparent fishing ground to be approached). From October 17th to the 21st, the same methodology was used to monitor the fishing activities of El Golfo de Santa Clara (SC), the other small fishing town within the vaquita distribution area, in the east coast of the upper Gulf of California in the State of Sonora, Mexico. Since every boat goes out and back once per day, making only one trip per day, we consider the number of trips as our measure of fishing effort.

Estimation of fishing effort

To estimate the fishing effort for the days that were not monitored and to cover the entire shrimp season, which was not done by D'Agrosa *et al*., it was necessary to address the different factors that could affect the number of trips conducted on a given day such as (9):

Tidal amplitude. Fishermen of the upper Gulf of California did not go out fishing when the difference between high tide and low tide on a given day is smaller than 2 m (9). Thus, the difference between high and low tide for the days of the study represented the tidal amplitude measure and data was collected using sea level data of Centro de Investigacion Cientifica y de Educacion Superior de Ensenada;

Wind speed. Fishermen did not go out to fish if the wind conditions represent a risk while fishing. Wind speed data was collected from the San Felipe meteorological station (Estacion Sinoptica Meteorologica) of the Mexican Meteorological System;

Day of the week. In the study by D'Agrosa *et al*., fishermen of El Golfo de Santa Clara did not go out fishing on Sundays (9). Thus, the number of trips conducted on a given day can be unpredictable due to the fact that fishermen don't go fishing during festivities, weekends, etc;

Date. As per CONAPESCA, shrimp productivity is higher during the first three months of the shrimp season (8). Catches decrease by the end of the season, assuming that the same occurs to the fishing effort;

Fishing town. Due to the fact that there was not enough data to incorporate into the model on the fishing effort monitored in El Golfo de Santa Clara, both towns (SF or SC) were considered as a factor.

To estimate the number of trips (λ) for the days that were not monitored, the factors influencing fishing effort were analyzed within the framework of a Generalized Linear Model (GLM), assuming a negative binomial distribution. That is we assumed that:

$$\lambda = e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{31} X_{31} + \beta_{32} X_{32} + \beta_4 X_4 + \beta_5 X_5}$$

Where e denotes the exponential function of the independent variables, X_1, X_2, X_4 y X_5 represented tidal amplitude, wind speed, town and date respectively, X_{31}

represented the rest of the days of the week and β_0, β_1, β_2, β_{31}, β_{32}, β_4 y β_5 states the estimated coefficients.

Four models with different combinations of the factors influencing fishing effort were essayed in order to select the best model, based on variance-covariance matrix as computed by the optimization routine of package AD Model Builder (10). Once the model was selected, a Bayesian Analysis approach was used to obtain posterior distributions of its parameters (11). Monte Carlo Markov Chain routine (MCMC) in ADMB was used for this purpose, which is based on an implementation of the Metropolis-Hastings algorithm (11).

There was no previous information on the parameters of the models, therefore we used uniform, semi-informative prior distributions. Every parameter was started at zero and 500,000 MCMC steps were used to construct posterior distributions. Convergence problems were inspected by plotting moving average and standard deviations against MCMC steps (requiring average and standard deviation to stabilize), MCMC run (showing a random walk instead of deviations to certain values), and histogram form of posterior distributions (showing well-formed tails and smooth contour).

Medians of every posterior distribution were used as point estimators of parameters. Percentiles were used to construct credibility intervals. MCMC chain was used to obtain posterior distributions of estimated number of trips for days with no monitoring effort, using observed values for variables as described before. The total fishing effort was then calculated as the sum of observed plus the estimated trips per day.

Mortality rates

There are only two specifically designed estimations of the vaquita abundance available in the literature. In 1997, the abundance of vaquitas was estimated to be 567 individuals and later in 2008, the abundance was estimated to be 245 vaquitas (13, 18). Using the point estimates, it means a 56.79% percent decline in 11 years, which translates to an average annual decline of about 7.36%. Using this average we constructed a table of expected vaquita abundances from 1997 to 2008, assuming the population was decreasing at a similar average annual rate prior to 1997 (Table 1). Also, in order to compare the results of this study and those of D'Agrosa *et al.*, the abundance and captured vaquitas were also estimated from 1992 to 1997 assuming the population was decreasing at a similar average annual rate (Table 1) (9).

During the last meeting of the Comite Internacional para la Recuperacion de la Vaquita (CIRVA), the vaquita abundance was estimated to be 97 individuals by 2014 (7). Using the same procedure as above, we estimated abundances from 2009 to 2013 with the average annual decrease rate calculated from 2008 and 2014 estimates. Based on the following demographic model the number of vaquitas that should have been captured (V_c) from 1997 to 2014 was estimated (Table 1).

$$Vc = N_t + \left[N_t * r\ (1 - \frac{N_t}{K})\right] - N_{t+1}$$

Where N_t stated the estimated abundance on a given year, N_{t+1} represented the estimated abundance the following year, K represented the carrying capacity of 5,015 vaquitas and r the intrinsic growth rate of the vaquita estimated to be 0.038 (13, 16). Subsequently, data in Table 1 was used to estimate mortality rates using the following equations:

$$M_{i(2013-2014)} = \frac{V_{c(2013-2014)}}{ET\ *\ (3/2)}$$

$$Mc = \frac{M_i}{V_{2013}}$$

Where *Mi* denotes the instant mortality rate (vaq/trip), which is defined for the period of study (2013-2014); *Mc* is the mortality rate *per capita* ($trips^{-1}$), *Vc* denotes the number of vaquitas that should have been captured during the period 2013-2014, *V* is the abundance of the vaquita population by 2013 and *ET* is the total fishing effort estimated. The latter is multiplied by 3/2 because the data obtained for the model only represents nine months of the year (2/3 of the fishing season) and assuming that from March to June the same number of trips are conducted by the fishermen the rest of the season.

Year	Abundance	Captured vaquitas
1992	830	87
1993	769	81
1994	713	76
1995	660	70
1996	612	65
1997	567	61
1998	525	56
1999	487	52
2000	451	49
2001	418	45
2002	387	42
2003	359	39
2004	332	36
2005	308	34
2006	285	31
2007	264	29
2008	245	27
2009	227	25
2010	210	39
2011	179	40
2012	146	32
2013	119	26
2014	97	UNK

Table 1: Abundance and captured vaquitas from 1992 to 2014. UNK= unknown.

Results

The artisanal fisheries of San Felipe were monitored from September 15 - December 14, 2013. In 72 monitored days, 4,079 trips were conducted by the artisanal fleet. In El Golfo de Santa Clara, the artisanal fisheries were monitored from October 17 - October 21, 2013 and 1,426 trips were conducted by the artisanal fleet in 5 days of observations.

Factors influencing fishing effort

Tidal amplitude was visually the main factor influencing fishing effort on a given day, followed by wind speed (Figure 1). When tidal amplitude increased, the number of trips conducted by the fishermen was greater and when wind speed decreased, a greater number of trips were observed. There were no significant differences between the day of the week and the number of trips conducted by the artisanal fleet (Figure 2).

Estimation of fishing effort for the days that were not monitored

Based on the variance-covariance matrix results, the model with tidal amplitude, wind speed, and day of the week was not selected because the variance of the parameters was above 32 million, therefore, the model with tidal amplitude, wind speed and town was selected as the best model. The link function of number of trips given the variables included in the selected model is:

$$\lambda = e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3}$$

Where *e* denotes the exponential function of the independent variables, X_1, X_2 y X_3 represent tidal amplitude, wind speed, and town effect and $\beta_0, \beta_1, \beta_2, \beta_3$ are the estimated coefficients.

There were no apparent problems of convergence after running the MCMC chain 500,000 times. The moving standard deviation and average stabilized since early in the chain and the run looks to travel in the sample space randomly along the walk. Figure 3 shows the posterior distributions of the coefficients of the parameters obtained after running the MCMC chain and Table 2 shows the point estimate (median of MCMC chain) of the coefficient for each parameter. The posterior distributions were symmetrical, with a similar form of a normal distribution.

For the days that were not monitored from September 15th 2013 to March 14th 2014, a total of 5,366 trips were estimated to be conducted by the artisanal fleet of San Felipe and 39,821 trips by the fishermen of El Golfo de Santa Clara (Table 3). Figure 4 shows the posterior distributions for the days with more and less number of estimated trips for both towns.

The total fishing effort estimated for the Upper Gulf, represented as the number of trips for the 2013-2014 fishing shrimp fishing season resulted in 50,693 trips (Figure 5). The fleet size at the beginning of the shrimp season of 2013 was assumed to be of 908 pangas (6). Thus, each panga made in average 51 trips per

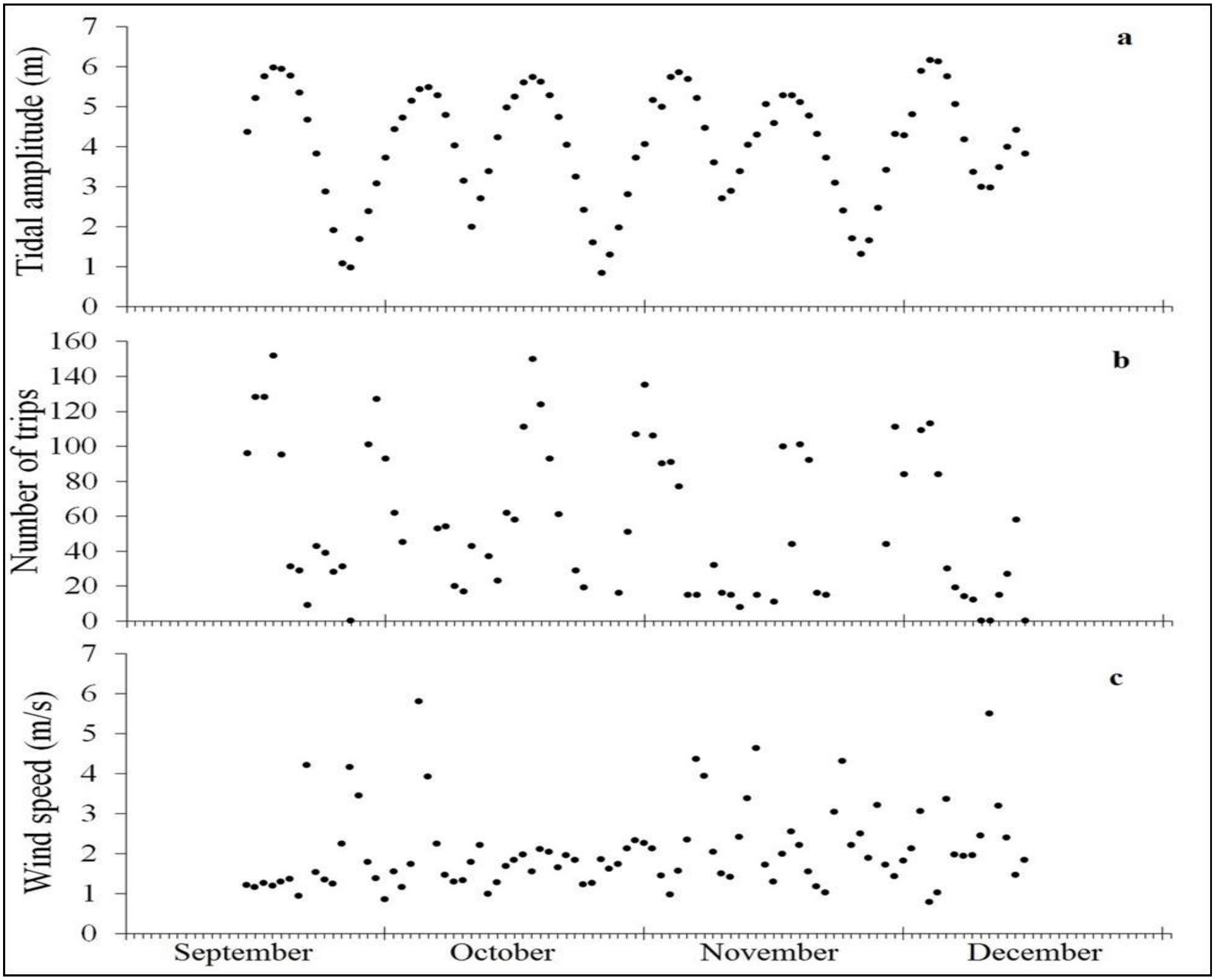

Figure 1: Daily raw datae regarding conditions and trips taken. Datae collected from September 15th to December 14th 2013 (a) tidal amplitude; (b): fishing effort; (c): wind speed. Each unit on the horizontal axis represents one day.

season.

The instantaneous mortality rate estimated for the 2013-2014 period was 0.00038 (95% I.C. 0.00036-0.00039) vaquitas/trip and the *per capita* mortality rate estimated was 0.00000315 trips^{-1} (95% I.C. 0.0000031-0.0000033).

Discussion

Incidental mortality, especially in gillnets, has been responsible for the decrease of the abundance of several porpoise species worldwide (14, 19, 22-24). Fishing effort represents a parameter that has made possible the quantification of the impact of fisheries in certain cetacean species (15). The information presented in this study represents the first update in twenty years documenting the dynamics and behavior of the Upper Gulf of California artisanal fishing activities to measure and describe the fishing effort impacting the vaquita population. The present study estimated only the fishing effort for the shrimp fishery and did not include the effort and mortality in illegal nets set for totoaba, an illegal fishery that has risen in the last couple of years.

Dynamic of the shrimp fishery

As seen in Figure 1, although the factors that define whether the artisanal fleet goes out fishing on a given day are clearly tidal amplitude and wind speed, we cannot disregard the fact that the behavior of the fishermen often determines the dynamic of the fishery on a given day. That is, in some occasions, the decision

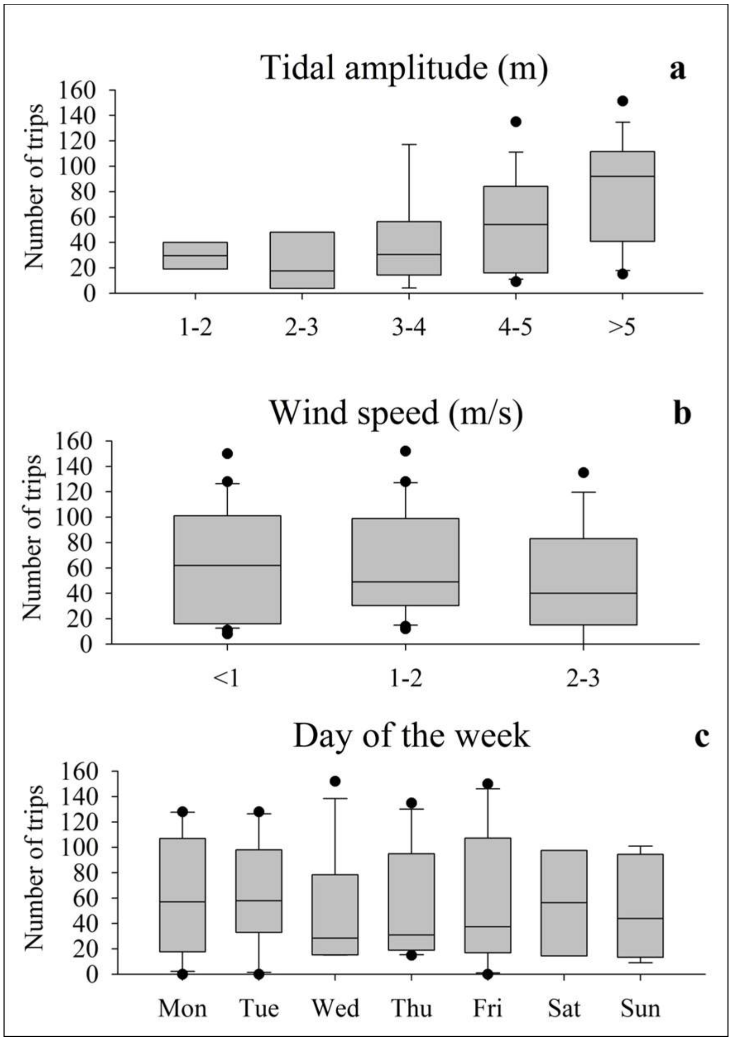

Figure 2. Distribution of the datae collected based on trips observed in San Felipe from September 15th to December 14th 2013 and its relationship with: (a) tidal amplitude; (b) wind speed and (c) day of the week.

to go out or to return early from fishing is not a mechanic decision, but a subjective one, far from the environmental factors that determine a work day, such as sport events, local or religious festivities, etc. There is also a strong communication between fishermen in San Felipe, regardless of the cooperative in which they worked. One fishermen once said that after two or three days of fishing, the word spreads around that the shrimp has been harvested and then they rest the next two or three days. Also when wind speed was strong, fishermen stayed on their pangas at the FONATUR Marina and waited until wind conditions changed or until other fishermen said the conditions were appropriate to go out

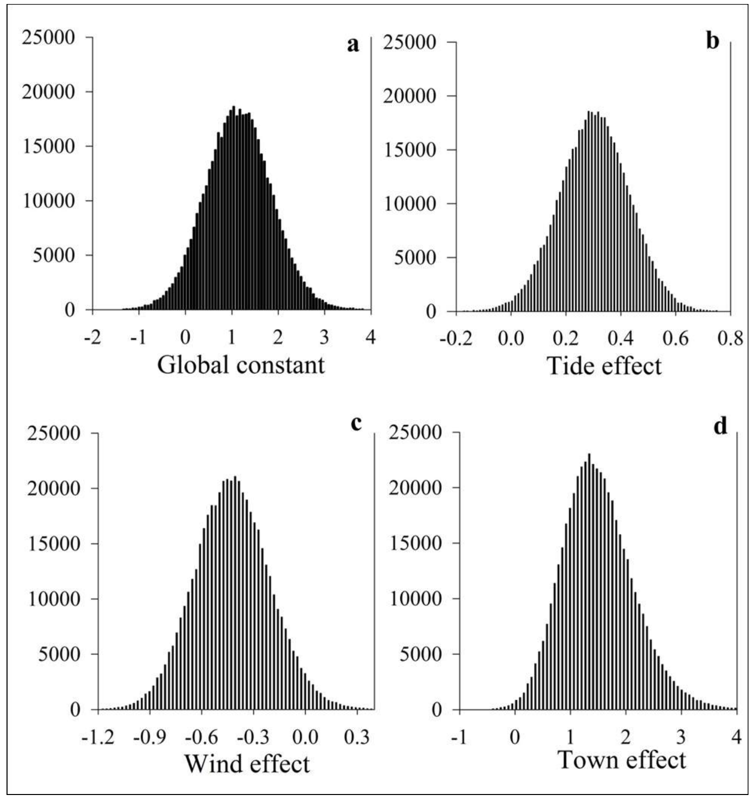

Figure 3. Posterior distributions of the estimated coefficients: (a) global constant, (b) tidal amplitude, (c) wind speed and (d) town. The median of each distribution represented the punctual value for each coefficient.

fishing.

By December, fishermen changed the direction of navigation. Specifically, during September and October they were observed coming back from the North. By late October fishermen would come back from the east and by late November and early December from the south. This could be due to the following factors; (a) the predominant wind circulation of the Upper Gulf has southeast winds during summer and northwest winds during winter. In the present study, the months of the sampling period covered both patterns (2); (b) shrimp tend to move to deeper water which transports the shrimp towards the south (4); (c) all reported that shrimp depletion often occurs when there are high levels of fishing effort (1). Thus, the mobility of the fishermen to the south by the end of November could have occurred because of the depletion of shrimp during the first months of the season or because of the empirical knowledge that has been gathered by the fishermen that the shrimp moves to the south.

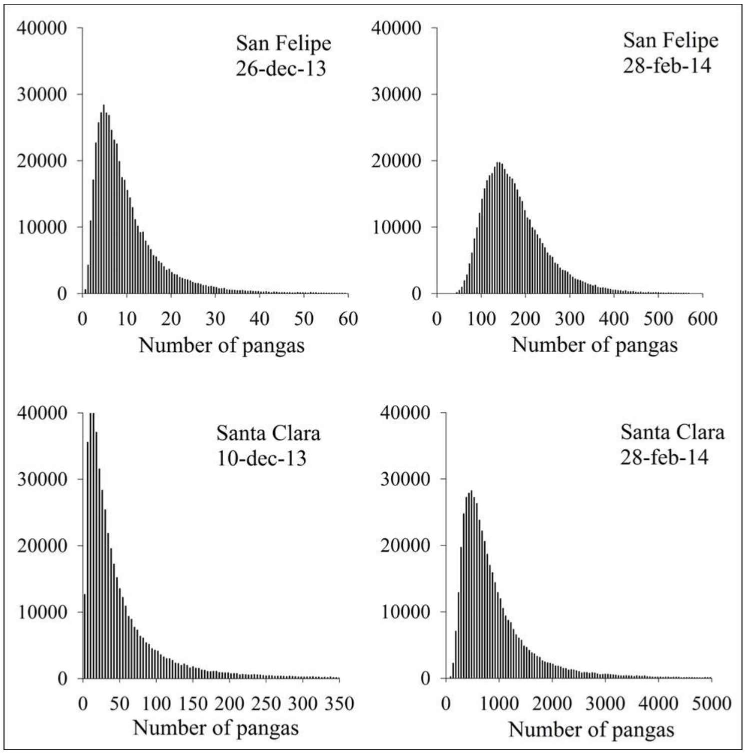

Figure 4. Posterior distributions of the fishing effort for the days with less (left) and most (right) number of trips estimated for San Felipe and El Golfo de Santa Clara.

Estimation of fishing effort

In 1995, D'Agrosa *et al*. reported that there were almost no fishing trips on Sundays while the present study demonstrated that fishing now does indeed occur on Sundays (Figure 2). This could represent a change in the artisanal fishermen behavior over the last twenty years. In 1993 the resource competition between fishermen was almost not existent, or maybe there were less cooperatives, resulting in lower rates of fishing effort. All this has changed and fishermen now use every opportunity to go out fishing, regardless of the day of the week.

The number of trips as a fishing effort measure has been acknowledged to be an important constituent to describe the interactions between the different components of the artisanal fisheries and a good indicator in places where there is lack of information and enforcement of fishing activities (19). As well, many authors have estimated the number of vaquitas that could have been captured on a given year, based on the size of the artisanal fleet under different scenarios (12, 17).

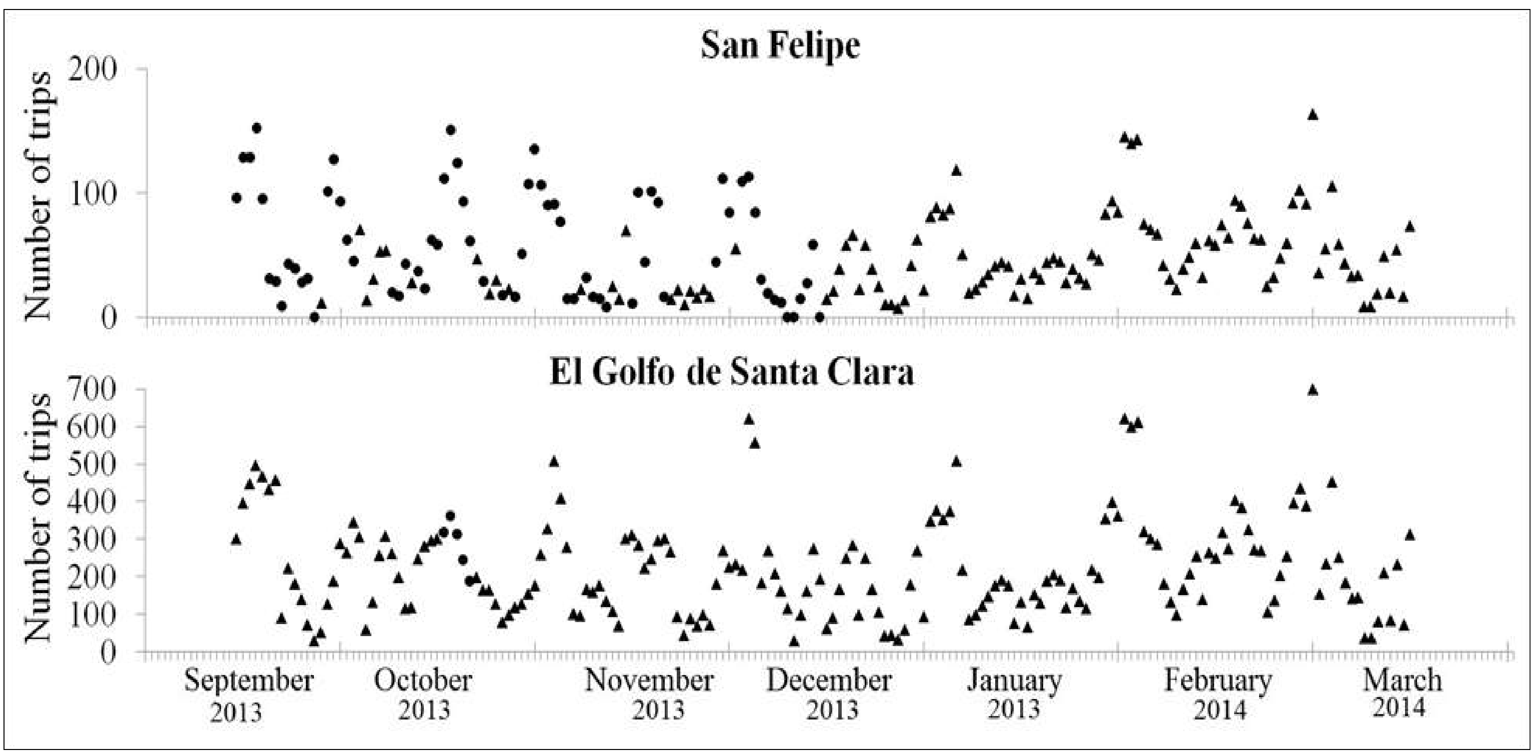

Figure 5. Observed (●) and estimated (▲) fishing effort for the 2013-2014 shrimp season of San Felipe and El Golfo de Santa Clara. In the horizontal axis, each unit represents one day.

Parameter coefficient	Point estimate	Credibility interval
β_0	1.1415	- 0.23791 , 2.56138
β_1	0.3040	0.05390 , 0.55020
β_2	0.4261	- 0.84226 , 0.01646
β_3	1.4527	0.37143 , 2.90951
r	0.6505	0.52632 , 0.78859

Table 2. Estimated coefficients for the parameters of the model.

	Point estimate	Credibility interval
San Felipe	5,366	3,164 - 9,991
El Golfo de Santa Clara	39,821	13,151 - 177,062
TOTAL	45,187	315 - 187,053

Table 3. Number of trips estimated for the Upper Gulf of California.

Morality rates

For the 1992-1995 period study by D'Agrosa *et al*., the vaquita population was estimated to be 830 individuals, resulting in a mortality rate of 1.19x10^{-5} trips^{-1} (9). There is a difference of one order in magnitude between the *per capita* mortality rate estimated in this study and the one estimated by D'Agrosa *et al*. in which the latter is higher (9).

These authors estimated that during the 1993-1994 period, around 9,000 trips were conducted by the artisanal fleet of the Upper Gulf, which could be an underestimation due to several factors. First, the *in situ* observations made in the study were conducted from February to August 1993. The shrimp fishery was the first to be monitored from late January to mid-March, resulting in the only fishery that was monitored intermittently. Thus, the fishery that was mostly represented in the model was sampled during the less productive months of the season, probably resulting in a underestimation of the fishing effort in El Golfo de Santa Clara.

In 1995 and later in 2012, the Scientific Committee of the International Whaling Commission (IWC) recommended that the incidental mortality of a porpoise such as *P. sinus* should not be greater than one-fourth of the potential rate of increase. This estimation has been used primarily with harbour porpoise (*Phocoena phocoena)* since this species has a similar growth rate to the vaquita. Therefore, the rate of increase of the harbour porpoise can be used to make mortality rate estimations for the vaquita (5, 13, 21).

Although the mortality rate estimated in the present study is nearly zero per set, when the number of trips estimated in more than 50,000 is taken into account, the mortality rate of almost zero becomes relevant. This is, if the number of vaquitas captured in a year is divided by the population size of that year the result is the mortality rate per year (5). Thus, for the 2013-2014 period, the number of captured vaquitas is calculated using the estimated mortality rate *per capita* (3.15 x 10^{-6} trips^{-1}), the estimated total number of trips for the 2013-2014 season (50,692 trips times 3/2 to estimate the number of trips for the entire year), and the vaquita abundance (119 individuals). Assuming that the vaquita mortality rate of 7.36% annual stayed the same from 1997 to 2008, the *P. sinus* abundance for the 2013-2014 period is 119 vaquitas. Thus, the number of captured vaquitas for the 2013-2014 period was estimated at 28 individuals. If this estimation is divided by the 119 estimated vaquitas, the result is an annual mortality rate of 24% of the population.

According to the last meeting of the Comité Internacional para la Recuperación de la Vaquita (CIRVA), held in July 2014, the best estimate of current abundance was 97 vaquitas, with an annual population decline of 18.5% from 2012 to 2014 (7). Therefore, the number of captured vaquitas in 2014 is 24 individuals.

Dividing this estimation by the 97 vaquitas estimated by CIRVA resulted in an annual mortality rate of 24%.

For both estimations, the vaquita mortality rate of 24% per year is six times its potential rate of increase (3.98%). The minimum viable population estimates the minimum number of individuals a population needs in order to be able to persist for a certain period in the future (3). A mortality rate of this magnitude suggests that the vaquita population could soon reach its minimum viable population size, decreasing any possibility of recovery. An immediate solution is to have the Mexican Government increase enforcement resources to ban gillnets and eliminate illegal fishing in the vaquita refuge. It is necessary to implement an alternative fishing gear that could benefit the local fishermen. Training and environmental education programs are required to teach local communities conservation strategies involving recovery. Vaquita population increase can only be achieved if all the involved organizations enforce strict conservation measures in collaboration with the government. The vaquita will soon be lost if by-catch is not eliminated immediately.

Less than 100 vaquitas now remain (7). Approximately 51,000 trips by the artisanal fleet were conducted, resulting on a mortality rate of more than 25 vaquitas per year. With a population growth rate of only 4%, the vaquita population is not capable of sustaining the current amount of fishing effort, particularly if the skiffs continue using gillnets as fishing gear. The vaquita can only recover if all gillnet fishing within its range is eliminated.

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