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RISK FACTORS AFFECTING THE VAQUITA (*PHOCOENA SINUS*)¹

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ABSTRACT

Despite the vaquita being commonly cited as one of the most endangered marine mammals in the world, there is still disagreement over which factors put the species at greatest risk of extinction. This lack of agreement hinders management decisions needed to reduce the risk to the species. To expedite decision-making we consider four major risk factors. Habitat alteration from reduced flow of the Colorado River does not currently appear to be a risk factor because productivity remains high in vaquita habitat. Pollutant loads are low and pose low to no risk. Reduced fitness from inbreeding depression

¹ Although we never enjoyed the privilege of working with Ken Norris, it is hard to imagine a marine mammalogist who has not been influenced by his work directly or indirectly. His influence is especially strong for those of us working with the vaquita. In 1958 mammalogists world-wide were able to read the description of a new species of porpoise from the Gulf of California (Norris and McFarland, 1958). Ken not only described it, from incomplete specimens, but also made clear that this new species was related to Burmeister's porpoise in South American waters more than to its closest geographical neighbor, the harbor porpoise in Californian waters. Many years later, 36 to be exact, Rosel *et al.* (1995) confirmed Ken's hypothesis using the most advanced molecular techniques. In this same paper Norris and McFarland hypothesized that speciation occurred through isolation in the Upper Gulf of California. These views are still accepted today. These examples illustrate Ken Norris' extraordinary understanding of natural history and biological processes. Ken kept his interest in vaquita biology and conservation his entire life and published other papers about the species. To the pioneer that Ken Norris was in the conservation of marine mammals, particularly in the case of the vaquita, we dedicate this paper about the conservation of this endemic porpoise from the Upper Gulf of California.

and loss of genetic variability are unlikely to pose high risk currently, though risk will increase if vaquitas remain at low abundance over long periods of time. Mortality resulting from fisheries bycatch poses high risk. Thus, short term management should not be hindered by uncertainty in estimating the risk of these factors, and primary conservation efforts should be directed towards immediate elimination of incidental fishery mortality.

Key words: risk factors, vaquita, *Phocoena sinus*, bycatch, pollution, inbreeding depression, productivity.

Vaquitas are vulnerable to extinction because they are naturally rare and have a very limited distribution with a single population. They were only recently scientifically described (Norris and McFarland 1958). In subsequent years little has been learned about their basic life history because they are difficult to find and study in the wild. Their limited distribution is demonstrated by sightings made in a 1993 survey that systematically covered the entire Gulf of California (Fig. 1, Gerrodette *et al.* 1995). Brownell (1986) evaluated all reported sightings and concluded that all confirmed sightings were within the northern Gulf in approximately the area shown in the inset of Figure 1. Vaquitas have been considered endangered by several authors (Barlow 1986, Perrin 1989, Silber 1990, Vidal 1995). Accordingly, the vaquita is one of only two marine cetaceans classified as Critically Endangered by the International Union for Conservation of Nature and Natural Resources (Red List of Threatened Animals 1996), and is listed as an endangered species in Appendix I of the Convention on International Trade in Endangered Species in 1979, the U.S. Endangered Species Act in 1985, and the Mexican list of rare and endangered vertebrate species (Diario Oficial de la Federación 1994). The most recent abundance estimate (1997) is 567 animals, with a 95% confidence interval from 177 to 1,073 (Jaramillo-Legorreta *et al.*, this issue). Further work is being done to estimate trends in abundance using these new data; however, a previous study estimated a decline of 17.7%/yr (95% CI = -43.2%, 19.3%, Barlow *et al.* 1997). To assist in management decisions required for the recovery of vaquitas, we review available data for each of four risk factors and consider what management actions are appropriate for each factor and whether further data will be likely to alter management decisions.

Habitat Alteration in the Gulf of California

Water flow into the Upper Gulf of California (see inset Fig. 1) from the Colorado River has been greatly reduced by diversion for agricultural purposes and human consumption since the early 1940s (Brownell 1982). Villa-Ramírez (1993) and Fleischer (1996) asserted that this drastic change in the environment is the major cause of decline of vaquitas by assuming reduced nutrients previously contributed by the Colorado River lead to a reduced carrying capacity. The primary question is whether the productivity of the northern Gulf of California has been significantly reduced since the 1940s.

There are no direct data on productivity prior to reduction of the Colorado

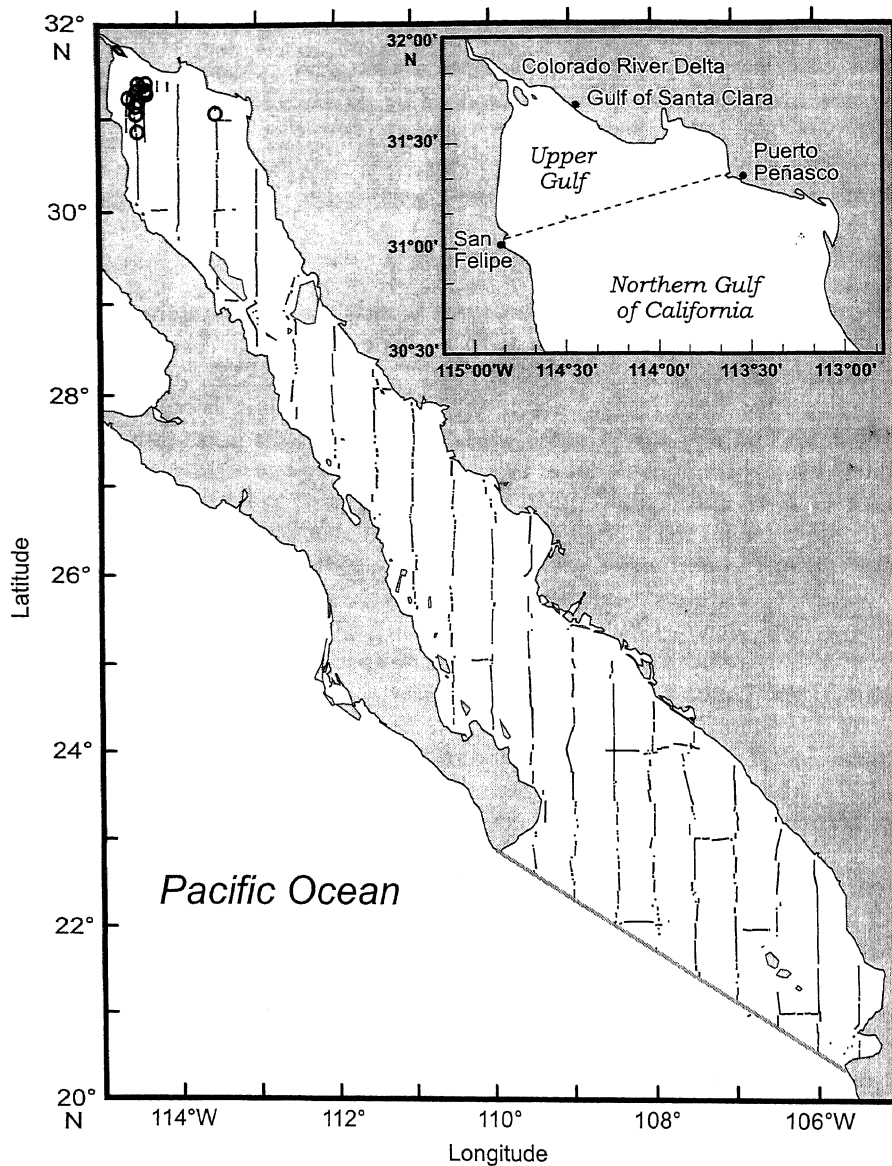


Figure 1. Map of Gulf of California with lines indicating vessel track-lines from 1993 survey (Gerrodette *et al.* 1995) and circles indicating vaquita sightings. Inset shows area within which all known vaquita sightings verified (Brownell 1986). Dashed line in inset is reserve boundary.

River flow. Therefore, we summarize Alvarez-Borrego's (1992) review and consider the evidence on whether the current level of productivity is low and whether this level of productivity is likely to be sustained. Using satellite imagery from the period from 1978 to 1986, Santamaria-del-Angel *et al.*

(1994) described the Upper Gulf as a region characterized by strong tidal mixing, high turbidity, and high nutrient concentrations especially in the northernmost part. Cupul-Magaña (1994) and Hernández-Ayón *et al.* (1993) using data since 1989 reported higher nutrient concentrations (NO_2^- , NO_3^- , PO_4^{3-} , SiO_2) in the Colorado River Delta than reported for most estuarine and non-estuarine environments. Higher than average nutrients were also reported for the Upper Gulf (Nieto García 1998). Nutrient concentrations were high throughout the year. Very high concentrations both of chlorophyll-*a* (Alvarez-Borrego 1992, Millán-Núñez 1992) and phytoplankton have been reported for upwelling areas in the Gulf (Zeitzschel 1969). Rates of primary productivity are about two to three times greater in the northern Gulf than rates in the open Atlantic or the open Pacific at similar latitudes (Zeitzschel 1969). Zooplankton biomass values are within the range reported in the literature for oceanic and estuarine waters (Farfán and Alvarez-Borrego 1992) with highest concentrations at the Colorado River delta. Zooplankton volumes (Cummings 1977) exceeded by a factor of two the values reported by Cushing (1969 in Cummings *op. cit.*) for upwelling regions such as Costa Rica or Peru.

Where do these nutrients originate? The great fertility of the northern Gulf has long been explained through oceanographic processes such as the exposure of nutrients to the surface through strong tidal mixing, convection processes due to cooling in the winter months and continuous upwelling throughout the year (Svedrup 1941 in Roden 1964, Cummings 1977, Alvarez-Borrego 1983, Alvarez-Borrego and Lara-Lara 1991). The relatively shallow (up to 200 m) northern Gulf of California is separated from the deeper southern Gulf (ranging to 3,000 m) by a series of islands that form a "waist" in terms of tidal flow (Roden and Emilsson 1979). Intense forcing by tides, winds, solar heating, and interaction with the open Pacific Ocean creates vigorous circulation in the Gulf (Alvarez-Borrego and Lara-Lara 1991). According to Alvarez-Borrego and Lara-Lara (1991) and Alvarez-Borrego (1983) it is all these processes that interact to make these waters such a fertile coastal oceanic system.

However, beyond these oceanographic explanations, in which input from the Colorado River plays a minor role, several other hypotheses have been proposed to help explain the fertility of the Upper Gulf. Hernández-Ayón *et al.* (1993) proposed that the nutrient input, specifically nitrate, could come from groundwater input from channels in the river delta. A second explanation for the high productivity involves continuing input from the Colorado River, not from direct flow but from erosion of accumulated nutrients in the delta. Cupul-Magaña (1994) has suggested that the reduction of freshwater flow decreased the supply of silt. During the formation of the delta large amounts of nutrients could have been trapped in interstitial water. Tidal currents (Glenn *et al.* 1996) continuously erode delta sediments. As the delta erodes the nutrients could be liberated into the water column (Cupul-Magaña 1994) thus acting as a source of nutrients even without the flow of the river. Because new silts are not deposited, the erosion causes a net loss which eventually could result in exhaustion of this nutrient source.

If productivity is primarily from large-scale oceanographic processes, then

no management actions to increase productivity are required because such oceanographic processes are not known to have changed. On the other hand, if productivity primarily originates from previously deposited delta nutrients, future actions may be needed to maintain the health of the ecosystem. Regardless, neither scenario yields evidence that current productivity levels pose a risk for vaquitas. Analysis of the stomach contents of 34 gillnet-caught specimens show that vaquitas are opportunistic feeders² (Pérez-Cortés 1996) like the harbor porpoise (*Phocoena phocoena*, Gaskin 1982). Thus, vaquitas are unlikely to be strongly affected by the decline of species dependent on freshwater input. None of the vaquitas taken from gillnets showed signs of emaciation, including mothers, calves and sub-adults, which are most likely to be stressed when food is limited. Because current productivity is high, we conclude that habitat alteration resulting from the reduction in Colorado River flow is currently a low risk factor, although long-term considerations should encourage research on the origination of nutrients within their critical habitat.

Pollutants

Because certain pollutants may compromise reproductive function and survival rates in marine mammals, there is potential risk presented by those chemicals that are commonly used in agricultural regions near the northern Gulf of California (the Imperial Valley, U.S.A. and the adjacent Mexicali Valley, Mexico) (Brownell 1982). In aquatic habitats in both areas, levels of DDT and other organochlorine pesticides exceed the high-concentration criterion (5 mg/g wet tissue) for fish (see Gutierrez-Galindo *et al.* 1988b) and clams (Guardado-Puentes 1976). Accordingly Guardado-Puentes (1976) suggested that the Mexicali Valley could be an important source of organochloride pollution for the northern Gulf of California.

Marine mammals are long-lived and occupy a high trophic level; consequently many populations show high concentrations of organic pollutants (Colborn and Smolen 1996) including harbor porpoises (Barlow 1986). Otterlind (1976) and Wolff (1982) attributed the reproductive disorders and population decline of harbor porpoise in the Baltic Sea to high PCB concentrations. In Dall's porpoise (*Phocoenoides dalli*) reduction of normal levels of the male sex hormone testosterone have been ascribed to high tissue levels of PCBs and DDE (Subramanian *et al.* 1987). Chlorinated hydrocarbons (DDT, Endrin-dioldrin group, and PCB) have been implicated in reducing reproduction and juvenile survival and as a cancer agent (Gaskin 1982).

In the northern Gulf of California Gutierrez-Galindo *et al.* (1988a) reported values for organochlorines 6–10 times lower than the concentrations reported by Guardado-Puentes (1976) for the Mexicali Valley using the same species (*Corbicula fluminea*) as a bioindicator. This decrease reflects a general decrease in the use of these chemicals in the last decade. In the Gulf of Santa Clara,

² Personal communication from L. T. Findley, Centro de Investigación en Alimentación y Desarrollo, A.C., Apartado Postal 284, Guaymas, Sonora, Mexico.

where vaquitas have been caught, residues of pp'DDE were 6–13 times lower than those reported for total DDT close to Santa Clara (Isla Montague) by Guardado-Puentes (1976). Gutierrez-Galindo *et al.* (1992) reported that the levels of chlorinated hydrocarbons measured in all the region under study are at least ten times below the tolerated limits for human consumption accepted by the United States Food and Drug Administration. Furthermore, they did not exceed the action levels for chlordane proposed by the National Academy of Science that constitute danger to the environment. Low levels of organochlorine residues were also found in birds from the northern Gulf (Mora and Anderson 1991), which agrees with low levels in tissues of several vaquitas. Calambokidis (1988) reported maximum values for total DDT and PCBs of 9.1 ppm and 0.02 ppm, respectively. V. Camacho³ found DDE with a concentration of 1 ppm in vaquita tissue. These values contrast with those reported by Otterlind (1976) for harbor porpoise of 130 ppm (DDT, most of which is DDE) and 126 ppm (PCBs), which he suggested caused the decline of this species in Swedish waters (Teilmann and Lowry 1996). Calambokidis (1988) concluded that the ratio of DDE to total DDT indicates that the source of DDT is not from recent applications of this pesticide, which agrees with what Gutierrez-Galindo *et al.* (1988a, b) reported for *Chione californiensis* and *Modiolus capax* in the Upper Gulf. Therefore, available data do not currently indicate hydrocarbon pesticides or PCBs are a threat to the survival of the remaining vaquita population. Thus, because other pollutants are less likely to compromise reproduction and mortality of marine mammals, pollutants currently present no risk to vaquitas.

Inbreeding Depression

Recent evidence for the lack of genetic variability among 43 vaquitas in the hypervariable region of mitochondrial DNA (Rosel and Rojas-Bracho, this issue) together with morphological abnormalities (Ortega-Ortiz 1993, Torres-Cosio 1995, Hohn *et al.* 1996) has raised doubts concerning the genetic viability of vaquitas. In fact, the question has been raised whether vaquitas are already doomed to extinction because of inbreeding depression. Here, we review what inbreeding and inbreeding depression are and how a species' viability is affected by these factors. We then consider the special case of vaquitas, which differs from most species in that they appear to have persisted as a naturally rare species. We conclude with a discussion of how inbreeding depression could affect the future of vaquitas.

Inbreeding is simply the inheritance of alleles that are identical by descent. The most common understanding of inbreeding is close mating within a family, such as the inheritance of a grandfather's allele which was passed to both his son and daughter who then produced an offspring and received that allele

³ Personal communication from V. Camacho, Department of Geochemistry, Instituto de Investigaciones Oceanológicas Universidad Autónoma de Baja California, Ensenada, Baja California.

from both parents. The same process occurs in very small populations, not necessarily from direct brother-sister matings but because the chance of mating with a related individual increases. A small population has a limited gene pool, so it becomes more likely that an individual will inherit two alleles identical by descent. This effect becomes magnified as the gene pool becomes even smaller, because some alleles may go extinct by random chance (genetic drift).

Inbreeding depression is a reduction in population growth rate caused by the expression of deleterious alleles. We emphasize that inbreeding depression is not a certain outcome of inbreeding. Studies of skeletal material revealed that most vaquitas possess a sixth digit in their pectoral fin (Ortega-Ortiz 1993), some have vertebral abnormalities (Torre-Cosio 1995), and some females have odd calcifications in their ovaries (Hohn *et al.* 1996). It is unknown whether this condition was present in the ancestral form or whether it is an uncommon trait fixed through genetic drift. However, if these conditions do not decrease population growth, then the conditions do not constitute inbreeding depression even if inbreeding may have caused these unusual physical features. For example, two females and one male sika deer (*Cervus nippon*) founded a population now numbering in the thousands in Killarney, Ireland. The males show bilateral asymmetry in antler size and thus display an unusual trait often caused by inbreeding (Hayden *et al.* 1994). The population, however, has grown at a high rate and is not, therefore, displaying inbreeding depression.

The importance of inbreeding depression in determining the survival of naturally small populations has recently been questioned (Lande 1988, Caughley 1994). Inbreeding depression cannot be assumed to be proportional to the mean inbreeding coefficient, because selection can operate to remove deleterious alleles during slow inbreeding such as is experienced by populations that are naturally small. Naturally rare populations have persisted despite inbreeding because it is likely that recessive alleles which cause a serious reduction in fitness will be selected out of the population. Rosel and Rojas-Bracho (this issue) review case studies where species/populations with very low genetic variability appear to be thriving. Studies of captive populations (Ralls *et al.* 1988) reveal high variability in different populations' response to rapid inbreeding ranging from no effect to very high effects. Experiments conducted with mice affirm this variable response and suggest that the history of inbreeding and the chance events determining which genes remain in the population play a major role in the response of a population to further inbreeding (Lacy and Ballou 1998).

All these studies recorded the response to rapid inbreeding. Inbreeding at a slow rate gives selection time to purge deleterious alleles (Lande 1988). Experiments with *Drosophila* (Ehiobu *et al.* 1989) showed evidence that lines inbred over many generations had higher fitness than rapidly inbred lines. Taylor and Rojas-Bracho (this issue) simulated vaquita population dynamics to see whether the current lack of variability in mtDNA was because of historic events or the recent decline. They found in most cases that either a population had already become fixed for one haplotype by 1940 or it retained what var-

iability it had through the period of recent decline. In fact, the simulations affirmed that vaquitas are likely a naturally small population because in the simulations only small populations became fixed for mtDNA by the process of genetic drift. Thus, whatever genetic variability existed in 1940 is likely to still be present in the modern population.

Nevertheless, the current abundance of vaquitas is now or will soon be low enough to cause immediate erosion of what genetic variability remains. Using examples of domestic breeding, Franklin (1980) estimated that populations were safe from immediate loss of genetic variability if the effective population size (N_e) > 50. Effective population size is a term geneticists use for an ideal population, which meets many assumptions not met in wild populations, such as the ability of every individual to reproduce with an equal chance of breeding with every other individual and no population fluctuations through time. The ratio of the effective abundance to the estimated total abundance has been estimated to range between 1/10 (Frankham 1995) and 1/3 (Nunney 1991, 1993). The current abundance of vaquitas has been estimated to be between 177 and 1,073 (Jaramillo-Legorreta *et al.*, this issue). Thus, the lower limit is in the range where we should worry about the effects of future inbreeding. Taylor and Rojas-Bracho (this issue) address the question of whether further inbreeding will doom vaquitas. They reject this doom hypothesis because some captive mammals have demonstrated no decrease in population growth rate resulting from inbreeding (Ralls and Ballou 1983, Ralls *et al.* 1988). They show that inbreeding depression does not necessarily cause a reduction in growth rate sufficient to halt positive population growth. By using a range of possible demographic parameters for vaquitas together with inbreeding levels found for captive animals (Ralls and Ballou 1983) they were able to conclude that the data required to refine estimated magnitudes for inbreeding depressions for vaquitas were not attainable.

Although vaquitas are probably not genetically doomed now, we cannot afford to be complacent about this risk factor. It appears that, as a naturally rare species, vaquitas already have low genetic variability. Genetic variability provides the ingredients for adaptation to environmental changes and challenges like disease. We have also learned from captive breeding and inbreeding experiments that a species' or population's response to inbreeding is highly variable. Thus, although vaquitas are good candidates for a species that could have purged much of its genetic load, we cannot predict with any certainty how they will respond to further inbreeding. Because vaquitas are vulnerable as a result of natural low genetic variability, it is even more important that the species be allowed to recover quickly.

Incidental Fishery Mortality

Like other marine mammals (Perrin *et al.* 1994), vaquitas are easily entangled in gillnets. The highest incidental kills of vaquitas have been in the large-mesh gillnets (15–30.5 cm) used to catch totoaba (*Totoaba macdonaldi*) (Vidal 1995, Villa-Ramírez 1976, Brownell 1983). Data are sketchy to esti-

mate the historical or current levels of incidental mortality in fishing operations (Barlow 1986). Brownell (1982) mentions a catch of 10 porpoises in one day in the early seventies. He suggests that the annual incidental kill in the upper Gulf for these years was in the range of tens to hundreds. Vidal (1995) tallied 110 vaquitas incidentally killed in gillnets since the early seventies. This figure should be considered minimal since not all entangled vaquitas are reported and monitoring effort has not been continuous. Of these 110 vaquitas, 102 were killed in gillnets, 72 of which died in nets set for totoaba.

The exploitation of totoaba started in the early twenties with spear, hook and line, and then gillnet. By the early forties modern nylon gillnets were in full use (Flanagan and Hendrickson 1976, Ruiz-Durá 1985). A recent summary of the history of this fishery is given by Cisneros-Mata *et al.* (1995). Villa-Ramírez (1976) reports a seaman who mentioned that around 1940, before the introduction of large fishing vessels and outboard motors, vaquitas were seen more frequently. The largest captures of totoaba were before 1956 with peak catches in 1942 (2,261 metric tons). San Felipe, close to some of the highest remaining densities of vaquitas, accounted for 40%–50% of the totoaba yield, followed by Santa Clara and Puerto Peñasco, which are further from current areas of high vaquita density. The fishery declined drastically after 1967 and was closed by the Mexican government in 1975 (Avalos de Haro and Mathews 1973, Flanagan and Hendrickson 1976, Magatagan *et al.* 1984, Ruiz-Durá 1985).

Illegal fishing continues and contributes not only to extinction threats for totoaba but also for vaquitas. Vaquitas also entangle in other gillnets, including nets set for sharks (Brownell 1982, Vidal 1995, D'Agrosa 1995). In fact, they are susceptible to entanglement in shrimp trawls and many different mesh sizes of nets used for different species (see description of D'Agrosa's study below). Although there are no estimates for incidental mortality in shrimp trawls (Norris and Prescott 1961, Brownell 1982, Barlow 1986, Vidal 1995), this mortality source may be significant especially for calves (Vidal *et al.* 1999). All the vaquitas entangled in shrimp trawls between 1985 and 1990 were probably calves or juveniles (Vidal 1995).

Indirect data on vaquita mortality in gillnets are available from an experimental fishery for totoaba, during which 682 sets were observed between 1983 and 1993 (Fleischer 1994). Four vaquitas were killed, resulting in a mortality rate of 0.0058 vaquitas/set. Gerrodette⁴ used Fleischer's data to calculate 58 vaquita deaths/year assuming (based on Fleischer's data): (1) a mean catch of 910,000 kg of totoaba per year between 1935 and 1965, (2) the catch rate has remained the same, *i.e.*, the number of totoaba sets/year = 910,000 kg/89.54 kg/set, and (3) 10,000 sets/year. Thus, although catching a vaquita is a rare event, when it is multiplied by the total fishing effort, the total kill becomes significant. In the Mexican Progress Report on Cetacean Research (1996) Fleischer reports a second study in which 632 sets were examined in

⁴ Personal communication from Tim Gerrodette, Southwest Fisheries Science Center, P. O. Box 271, La Jolla, CA 92038-0271, U.S.A.

1993 without any vaquita kills. Recall that only four kills were observed in the first decade-long study. Given that vaquita mortality is a very rare event, all mortality estimates should be accompanied by estimates of precision, preferably confidence limits. The probability of observing no mortality for the 632 sets using a mortality rate of 0.0058 is 0.025. It is unclear why these numbers are contradictory but it could be because of the imprecise estimate of mortality rate for both data sets, because such small numbers of sets were observed and mortality is a rare event.

Much more fishing effort was observed in a study specifically designed to estimate the incidental mortality of vaquitas (D'Agrosa 1995). She monitored the fishing effort and mortality of vaquitas between January 1993 and April 1994 in the Gulf of Santa Clara, Sonora. Fishing nets (with mesh size) monitored were: chano (*Micropogonias megalops*), 10–11 cm; chinchorro de linea for shrimp (*Penaeus* spp.), 7 cm; sharks, 15 cm; macarela and sierra (*Scomberomorus* spp.), 7.6 cm (D'Agrosa 1995). Fishing effort was the number of fishing trips per day. The data were analyzed within the Generalized Linear Models framework. Eleven vaquitas died in the 1,113 observed fishing trips. Vaquitas were entangled in gillnets with mesh size that varied from 7 cm to 15 cm. Data were separated into two categories: those obtained (1) only by onboard observers and (2) those combined from both interviews with fishermen and reports from onboard observers. The estimated mortality for the first category was 84 vaquitas/year (95% CI: 14, 155) and for the latter 39 (95% CI: 14, 93).

It is highly unlikely that current mortality levels can be sustained. For example, if we consider the most optimistic scenario and use the lowest mortality estimate from only a single village and the current best abundance estimate, we get a human-caused mortality rate of 0.07 (39/567). To sustain such a mortality rate, vaquitas would need a high population growth rate. Because demographic data for vaquitas are poor, we cannot estimate their maximum growth rate, but we can examine rates for other cetaceans. Comparative population growth rate estimates are: 0.025–0.029 for killer whales (*Orcinus orca*) (Olesiuk *et al.* 1990, Brault and Caswell 1993), 0.02 for spinner dolphins (*Stenella longirostris orientales*) (Wade 1994), 0.04 for spotted dolphins (*Stenella attenuata*) (Wade 1994), 0.07 for humpback whales (*Megaptera novaeangliae*) (Barlow and Clapham 1997) and 0.03 for gray whales (*Eschrichtius robustus*) (Buckland *et al.* 1993). Because it is unlikely that any of these cetaceans could sustain a mortality rate of 0.07, by analogy it is unlikely that vaquitas can withstand such pressure. Even if we consider the most optimistic scenario and use the lowest mortality estimate (39) with the highest abundance estimate (1,073), the resulting mortality would result in such a high mortality rate (0.036) that vaquita could go extinct or would be reduced to such low levels that the danger common to very small populations could lead to eventual extinction.

To illustrate how much time remains for conservation actions given likely current incidental fishing mortality, we present several possibilities about future vaquita abundance. Figure 2 shows vaquita abundance in years since 1997 for different potential population growth rates using the current best estimate of abundance. Table 1 gives plausible mortality rates using all estimates of

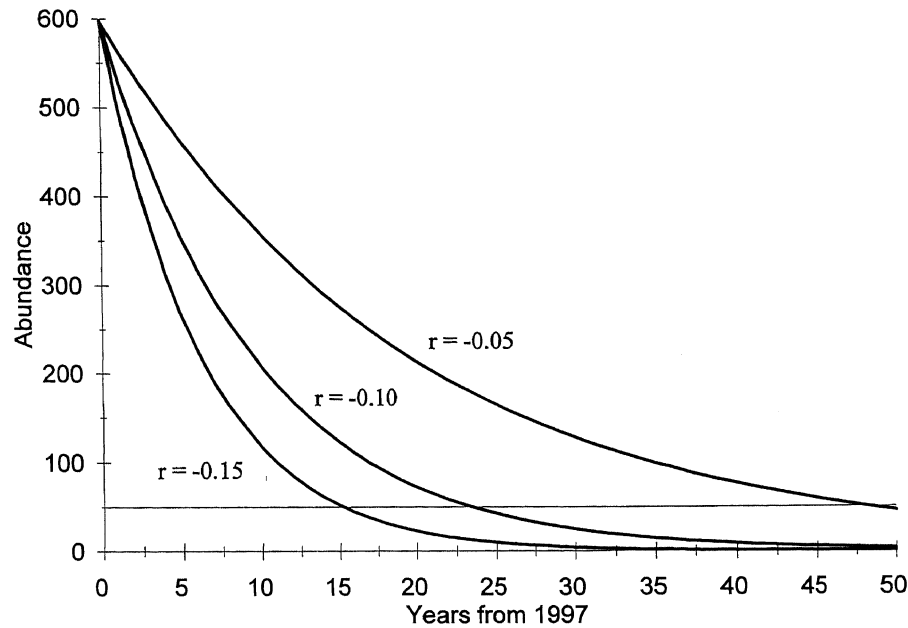


Figure 2. Abundance through time (shown in years from the most recent survey in 1997) for population growth rates (r) of -0.05 , -0.10 , and -0.15 . Each trajectory starts near the current best estimate of abundance. Horizontal line represents critical abundance of 50.

abundance (Jaramillo-Legorreta *et al.*, this issue; Barlow *et al.* 1997) and mortality from D'Agrosa (1995) estimated by two techniques. Recall that D'Agrosa's study (1995) considered only a single village and thus almost certainly underestimates the total mortality. We therefore chose to show population growth rates that ranged between $r = -0.05$ and $r = -0.15$. Although even greater rates of decline are plausible, it is clear that using a decline of -0.15 is sufficient to make the point that extinction is likely in a very short

Table 1. Mortality rates for mean abundance estimates from five different surveys with coefficients of variation in parentheses (Jaramillo-Legorreta *et al.* this issue, Barlow *et al.* 1997) and two estimates of mortality made using different techniques (D'Agrosa 1995).

Year	Type of survey	Abundance	Mortality rates	
			Mortality = 39	Mortality = 84
1986-1988	boat	503 (0.32)	0.08	0.17
1988-1989	aerial	855 (0.43)	0.05	0.10
1991	aerial	572 (1.41)	0.07	0.14
1993	ship	224 (0.30)	0.17	0.38
1997	ship	567 (0.51)	0.07	0.15

time without conservation action. We also show a horizontal line representing a critical abundance of 50 because once populations become this small, they face many more risk factors, including demographic stochasticity and inbreeding depression. They are therefore much more vulnerable and will likely decline even faster. Note that using our best estimate of abundance together with a mortality of 89 based on a single village yields a growth rate close to $r = -0.15$ (Table 1), which leaves about 15 yr before the highly risky $n = 50$ is reached. Such reasoning is precisely why the vaquita is listed as Critically Endangered by the IUCN red data list. Although the choice of any particular number is arbitrary, any scenario results in the conclusion that conservation action must be immediate.

CONCLUSIONS

This review reveals mortality from fisheries as the greatest immediate risk for vaquitas. The secondary effects of fishing in the Northern Gulf, such as direct and indirect effect of bycatch on prey species and alterations of the benthic habitat by repeated and intense trawling, are unknown and of concern. However, it is likely that any management actions taken to reduce direct kills of vaquitas by fishing activities will also affect these potential indirect threats to the prey and habitat quality of vaquitas. Pollution appears not to be a risk. Reduction of the flow of the Colorado River does not appear to have sufficiently reduced current productivity to pose a short-term risk to vaquitas. Inbreeding is likely to be a factor in vaquita biology but there is no evidence that inbreeding depression (causing a reduction in the population growth rate) should currently be a risk factor. There is no basis for considering vaquitas doomed because of lack of genetic variability.

What management actions can reduce the immediate risk to vaquitas? Within the next five years it is unlikely that any degradation of the habitat can be reversed. It is not even clear what actions, if any, would change the nutrient future of this region. No action can be taken to change vaquita genetics except returning abundance to higher levels to preserve what genetic variability vaquitas have maintained. It is clear that the only action that can be taken to save this species is an immediate large reduction or elimination of incidental mortality due to fishing, which will require both new regulations and strong enforcement.

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LITERATURE CITED

- ALVAREZ-BORREGO, S. 1983. Gulf of California. Pages 427–449 in B. H. Ketchum, ed. Estuaries and enclosed seas. Elsevier Scientific Publication Company, Amsterdam.
- ALVAREZ-BORREGO, S. 1992. Upper Gulf of California, the small habitat of the vaquita dolphin (*Phocoena sinus*). Current Crisis in Marine Mammal Management: US and Mexican Perspectives. Sixth Conference in the UC MEXUS Series, Critical Issues in US-México Relations. San Diego, CA. 19 pp. Available from Biblioteca, Centro de Investigación Científica y Educación Superior de Ensenada, Baja California (CICESE). Apartado Postal 2732, 22800 Ensenada Baja California, México.
- ALVAREZ-BORREGO, S., AND J. R. LARA-LARA. 1991. The physical environment and primary productivity of the Gulf of California. Pages 555–567 in B. R. T. Simoneit and J. P. Dauphin, eds. The Gulf and peninsular province of the Californias. American Association of Petrologists and Geologists Memoir 47.
- AVALOS DE HARO, AND C. P. MATHEWS. 1973. Pesquerías. Pages 365–394 in Estudio químico sobre la contaminación por insecticidas en la desembocadura del Río Colorado. Tomo II. Reporte Final a la Dirección de Acuicultura de la Secretaría de Recursos Hidráulicos. Universidad Autónoma de Baja California, Ensenada, Baja California, México. Available from Biblioteca, Universidad Autónoma de Baja California (UABC), Km 103 Carretera Tijuana-Ensenada, Ensenada 22800 Baja California, México.
- BARLOW, J. 1986. Factors affecting the recovery of *Phocoena sinus* the vaquita or Gulf of California harbor porpoise. US National Marine Fisheries Service Center Administrative Report SWFSC Administrative Report No LJ-86-37 (unpublished) 19 pp. Available from SWFSC, P. O. Box 271, La Jolla CA 92038.
- BARLOW, J., AND P. J. CLAPHAM. 1997. A new birth-interval approach to estimating demographic parameters for humpback whales. *Ecology* 78:535–546.
- BARLOW, J., T. GERRODETTE AND G. SILBER. 1997. First estimates of vaquita abundance. *Marine Mammal Science* 13:44–58.
- BRAULT, S., AND H. CASWELL. 1993. Pod-specific demography of killer whales (*Orcinus orca*). *Ecology* 74:1444–1454.
- BROWNELL, R. L., JR. 1982. Status of the cochito, *Phocoena sinus*, in the Gulf of California. Fisheries and Agriculture Organization Advisory Committee on marine resources research. Mammals of the Seas: Small cetaceans, seals, sirenians, and otters. Fisheries and Agriculture Organization, Fisheries Series 4:85–90.
- BROWNELL, R. L., JR. 1983. *Phocoena sinus*. *Mammalian Species* 198:1–3.
- BROWNELL, R. L., JR. 1986. Distribution of the vaquita, *Phocoena sinus*, in Mexican waters. *Marine Mammal Science* 2:299–305.
- BUCKLAND, S. T., J. M. BREIWK, K. L. CATTANACH AND J. L. LAAKE. 1993. Estimated population size of the California gray whale. *Marine Mammal Science* 9:235–249.
- CALAMBOKIDIS, J. 1988. Chlorinated hydrocarbons in the Gulf of California harbor porpoise (*Phocoena sinus*). Final Contract Report MM4465846-3 to the U.S. Marine Mammal Commission. Available from Cascadia Research Collective, 218½ W. Fourth Ave., Olympia, WA 98501.
- CAUGHLEY, G. 1994. Directions in conservation biology. *Journal of Animal Ecology* 63:215–244.
- CISNEROS-MATA, M. A., G. MONTEMAYOR-LÓPEZ AND M. J. ROMÁN-RODRÍGUEZ. 1995. Life history and conservation of *Totoaba macdonaldi*. *Conservation Biology* 9:806–814.
- COLBORN, T., AND M. J. SMOLEN. 1996. Epidemiological analysis of persistent organochlorine contaminants in cetaceans. *Reviews of Environmental Contamination and Toxicology* 146:91–172.
- CUMMINGS, J. A. 1977. Seasonal and aerial variation of zooplankton standing stocks in the Northern Gulf of California. M.Sc. thesis, University of Arizona, Tucson, AZ. 61 pp.

- CUPUL-MAGAÑA, L. A. 1994. Flujos de sedimentos en suspensión y de nutrientes en la cuenca estuarina del Río Colorado. Tesis de Maestría. Universidad Autónoma de Baja California. Facultad de Ciencias Marinas, Ensenada, Baja California, Mexico. 117 pp.
- D'AGROSA, C. E. 1995. Mortalidad incidental de la vaquita (*Phocoena sinus*) en actividades pesqueras del alto Golfo de California, México, 1993-94. Tesis de Maestría en Ciencias, Instituto Tecnológico y de Estudios Superiores de Monterrey, Guaymas, Sonora, México. 112 pp.
- EHIÖBU, N. G., M. E. GODDARD AND J. F. TAYLOR. 1989. Effect of rate of inbreeding on inbreeding depression in *Drosophila melanogaster*. *Theoretical Applications of Genetics* 77:123-127.
- FARFÁN, C., AND S. ALVAREZ-BORRERO. 1992. Zooplankton biomass of the northernmost Gulf of California. *Ciencias Marinas* 18:17-36.
- FLANAGAN, C. A., AND J. R. HENDRICKSON. 1976. Observations on the commercial fishery and reproductive biology of the totoaba, *Cynoscion macdonaldi*, in the northern Gulf of California. *Fishery Bulletin, U.S.* 74:531-544.
- FLEISCHER, L. A. 1994. Análisis de la mortalidad incidental de la vaquita, *Phocoena sinus*. Historia y actualidad. Informe final al Comité Técnico Para la Preservación de la Vaquita y la Totoaba. (unpublished). 20 pp. Available from Biblioteca Centro Regional de Investigaciones Pesqueras (CRIP) de la Paz, Instituto Nacional de la Pesca (INP). Km1. Carretera a Pichilingue, 23000 La Paz, Baja California Sur, México.
- FLEISCHER, L. A. 1996. Mexico. Progress report on cetacean research, April 1994 to March 1995. Report of the International Whaling Commission 46:262-264.
- FRANKHAM, R. 1995. Effective population size/adult population size ratios in wildlife: A review. *Genetical Research* 66:95-107.
- FRANKLIN, I. R. 1980. Evolutionary change in small populations. Pages 135-150 in M. E. Soulé and B. A. Wilcox, eds. *Conservation biology: An evolutionary-ecological perspective*. Sinauer Associates, Sunderland, MA.
- GASKIN, D. E. 1982. *The ecology of whales and dolphins*. Heinemann Educational Books, London.
- GERRODETTE, T., L. A. FLEISCHER, H. PÉREZ-CORTÉS AND B. VILLA-RAMÍREZ. 1995. Distribution of the vaquita, *Phocoena sinus*, based on sightings from systematic surveys. Report of the International Whaling Commission: (Special Issue 16):272-281.
- GLENN, P. E., C. LEE, R. FELGER AND S. ZENGEL. 1996. Effects of the water management on the wetlands of the Colorado River Delta, Mexico. *Conservation Biology* 10: 1175-1186.
- GUARDADO-PUENTES, J. 1976. Concentraciones de DDT y sus metabolitos en el Valle de Mexicali y Alto Golfo de California. *CalCOFI Report* 18:73-80.
- GUTIERREZ-GALINDO, E. A., G. FLORES-MUÑOZ AND J. VILLAESCUSA-CELAYA. 1988a. Chlorinated hydrocarbons in molluscs of the Mexicali Valley and the Upper Gulf of California. *Ciencias Marinas* 14:91-113.
- GUTIERREZ-GALINDO, E. A., G. FLORES-MUÑOZ, M. F. VILLA-ANDRADE AND J. VILLAESCUSA-CELAYA. 1988b. Organochlorine insecticides in fishes from the Mexicali Valley, Baja California, Mexico. *Ciencias Marinas* 14:1-22.
- GUTIERREZ-GALINDO, E. A., G. FLORES-MUÑOZ, M. L. ORTEGA-GARCIA AND J. VILLAESCUSA-CELAYA. 1992. Pesticidas en las aguas costeras del Golfo de California: Programa de vigilancia con mejillón 1987-1988. *Ciencias Marinas* 18:77-99.
- HAYDEN, T. J., J. M. LYNCH, AND G. O'CORRY-CROWE. 1994. Antler growth and morphology in a feral sika deer (*Cervus nippon*) population in Killarney, Ireland. *Journal of Zoology, London* 232:21-35.
- HERNÁNDEZ-AYÓN, J. M., M. S. GALINDO-BECT, B. P. FLORES-BÁEZ AND S. ALVAREZ-BORRERO. 1993. Nutrient concentrations are high in the turbid waters of the Colorado River Delta. *Estuarine, Coastal and Shelf Sciences* 37:593-602.

- HOHN, A. A., A. J. READ, S. FERNANDEZ, O. VIDAL AND L. T. FINDLEY. 1996. Life history of the vaquita. *Journal of Zoology*, London 239:235–251.
- LACY, R. C., AND J. D. BALLOU. 1998. Effectiveness of selection in reducing the genetic load in populations of *Peromyscus polionotus* during generations of inbreeding. *Evolution* 52:900–909.
- JARAMILLO-LEGORRETA, A. M., L. ROJAS-BRACHO AND T. GERRODETTE. 1999. A new abundance estimate for vaquitas: First step for recovery. *Marine Mammal Science* 15:957–973.
- LANDE, R. 1988. Genetics and demography in biological conservation. *Science* 241:1455–1460.
- MAGATAGAN, M. D., E. H. BOYER AND B. VILLA-RAMÍREZ. 1984. Revisión del estado que guarda *Phocoena sinus* Norris and MacFarland y descripción de tres nuevos ejemplares. *Annales del Instituto de Biología, Universidad Nacional Autónoma de México* 55:271–294.
- MILLÁN-NÚÑEZ, E. 1992. Spatial distribution of the phytoplankton in the Northern Gulf of California. *Ciencias Marinas* 18:101–117.
- MORA, M. A., AND D. W. ANDERSON. 1991. Seasonal and geographical variation of organochlorine residues in birds from northwest Mexico. *Archives of Environmental Contaminants and Toxicology* 21:541–548.
- NIETO GARCÍA, E. 1998. Nutrientes en el norte del Golfo de California durante condiciones estuarinas y antiestuarinas. Tesis de Maestría, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Baja California. 130 pp.
- NORRIS, K. S., AND W. N. McFARLAND. 1958. A new harbor porpoise of the genus *Phocoena* from the Gulf of California. *Journal of Mammalogy* 39:22–39.
- NORRIS, K. S., AND J. H. PRESCOTT. 1961. Observations on Pacific cetaceans of California and Mexican waters. *University of California Publications in Zoology* 63:291–401.
- NUNNEY, L. 1991. The influence of age structure and fecundity on effective population size. *Proceedings of the Royal Society, London. Series B. Biological Science* 246:71–76.
- NUNNEY, L. 1993. The influence of mating system and overlapping generations on effective population size. *Evolution* 47:1329–1341.
- OLESIUK, P. F., M. A. BIGG AND G. M. ELLIS. 1990. Life history and population dynamics of resident killer whales (*Orcinus orca*) in the coastal waters of British Columbia and Washington State. Report of the International Whaling Commission (Special Issue 12):209–243.
- ORTEGA-ORTÍZ, J. 1993. Descripción osteológica de la aleta pectoral de la vaquita *Phocoena sinus* (Cetacea:Phocoenidae). Tesis de Licenciatura. Escuela Nacional de Estudios Profesionales (ENEP), Iztacala, Universidad Nacional Autónoma de México (UNAM). 46 pp.
- OTTERLIND, G. 1976. The harbour porpoise (*Phocoena phocoena*) endangered in Swedish waters. *Ices C.M.* 1976/N:16.
- PÉREZ-CORTÉS H. 1996. Contribución al conocimiento de la biología de la vaquita, *Phocoena sinus*. Tesis de Maestría, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México. 68 pp.
- PERRIN, W. F. 1989. Dolphins, porpoises and whales—an action plan for the conservation of biological diversity: 1988–1992. IUCN Gland, Switzerland. 173 pp.
- PERRIN, W. F., G. P. DONOVAN AND J. BARLOW. 1994. Gillnets and cetaceans. Report of the International Whaling Commission (Special Issue 15).
- RALLS, K., AND J. BALLOU. 1983. Extinctions: Lessons from zoos. Pages 164–183 in C. M. Schoenwald-Cox, S. M. Chambers, B. MacBryde and L. Thomas, eds. *Genetics and conservation: A reference for managing wild animal and plant populations*. The Benjamin/Cummings Publishing Co. Menlo Park, CA.
- RALLS, K., J. BALLOU AND A. TEMPLETON. 1988. Estimates of lethal equivalents and the cost of inbreeding in mammals. *Conservation Biology* 2:185–193.

- RODEN, G. I. 1964. Oceanographic aspects of the Gulf of California. Pages 30–58 in T. H. Van Andel, G. G. Shore, Jr., eds. Marine geology of the Gulf of California: A symposium. of American Petrologists and Geologists, Memoir 3.
- RODEN, G. I., AND I. EMILSSON. 1979. Physical oceanography of the Gulf of California. Pages 1–46 in A. Ayala-Castañares, P. B. Phleger, R. Schwartzlose and A. Laguarda. Simposio El Golfo de California. Universidad Nacional Autónoma de México (UNAM). Available from Biblioteca del Instituto de Ciencias del Mar y Limnología (ICMyL), UNAM. Ciudad Universitaria, Circuito Interior. Copilco Universidad, México, Distrito Federal, 04510 México.
- ROSEL, P., AND L. ROJAS-BRACHO. 1999. Mitochondrial DNA variation in the critically endangered vaquita, *Phocoena sinus*. Marine Mammal Science 15:990–1003.
- RUIZ-DURÁ, M. F. 1985. Recursos pesqueros de las costas de México. Editorial Limusa, México.
- SANTAMARÍA-DEL-ANGEL, E., S. ALVAREZ-BORREGO AND F. E. MULLER-KRAGER. 1994. Gulf of California biogeographic regions based on coastal zone color scanner imagery. Journal of Geophysical Research 99:7411–7421.
- SILBER, G. K. 1990. Occurrence and distribution of the vaquita *Phocoena sinus* in the northern Gulf of California. Fishery Bulletin, U.S. 88:339–346.
- SUBRAMANIAN, AN., S. TANABE, R. TATSUKAWA, S. SAITO AND N. MIYAZAKI. 1987. Reduction in the testosterone levels by PCBs and DDE in Dall's porpoises of northwestern North Pacific. Marine Pollution Bulletin 18:643–646.
- TAYLOR, B., AND L. ROJAS-BRACHO. Examining the risk of inbreeding depression in a naturally rare cetacean, the vaquita (*Phocoena sinus*). Marine Mammal Science 15: 1004–1029.
- TEILMANN, J., AND N. LOWRY. 1996. Status of the harbour porpoise (*Phocoena phocoena*) in Danish waters. Report of the International Whaling Commission 46: 619–625.
- TORRE-COSIO, J. 1995. Descripción del esqueleto, dimorfismo sexual y crecimiento alométrico en el cráneo de la vaquita, *Phocoena sinus* (Cetacea: Phocoenidae). Masters thesis, Instituto Tecnológico y de Estudios Superiores de Monterrey–Campus Guaymas. 183 pp.
- VIDAL, O. 1995. Population biology and exploitation of the vaquita, *Phocoena sinus*. Report of the International Whaling Commission (Special Issue 16):247–272.
- VIDAL, O., R. L. BROWNELL JR. AND L. T. FINDLEY. 1999. Vaquita (*Phocoena sinus*) Norris and McFarland, 1958. Pages 357–378 in S. H. Ridgway and R. Harrison, eds. Handbook of marine mammals. Volume 6. The second book of dolphins and porpoises. Academic Press, London.
- VILLA-RAMÍREZ, B. 1976. Report on the status of *Phocoena sinus*, Norris and McFarland, 1958, in the Gulf of California. Annales del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología 47:203–208.
- VILLA-RAMÍREZ, B. 1993. Recovery plan for the vaquita, *Phocoena sinus*. NTIS Report PB93–169415. Report to the U.S. Marine Mammal Commission, 1825 Connecticut Ave. N.W., Washington, DC 20009. 36 pp.
- WADE, P. R. 1994. Abundance and population dynamics of two eastern Pacific dolphins, *Stenella attenuata* and *Stenella longirostris orientalis*. Ph.D. dissertation, Scripps Institution of Oceanography, University of California, San Diego, CA. 255 pp.
- WOLFF, W. J. 1982. The status of marine mammals in the Wadden Sea area. Pages 7–14 in P. J. H. Reijnders and W. J. Wolff, eds. Marine mammals of the Wadden Sea. A. A. Balkema, Rotterdam.
- ZEITZSCHEL, B. 1969. Primary productivity in the Gulf of California. Marine Biology 3:201–207.

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