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State of knowledge of the population of the vaquita (*Phocoena sinus*) from the Upper Gulf of California: a bibliometric analysis

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The state of scientific knowledge about the vaquita, *Phocoena sinus*, is presented, a critically endangered endemic species of the Upper Gulf of California, Mexico. Several bibliographic repositories were explored, selecting Web of Science because it considers the Science Citation Index as a selection criterion. A bibliometric and bibliographic analysis of the literature was carried out. A network of associations was built based on the co-occurrence of sets of keywords, which reflect the relevance of the research topics discussed. Two sets stand out: population and conservation. Unaddressed topics are also identified, such as trophic interdependencies, ecosystem, effects of the environment and climate patterns. Regarding the population, topics such as changes in abundance, vulnerability, distribution and current habitat have been addressed. In terms of conservation, the monotonic decrease in the size of the population stands out, the management aimed at stopping this decrease and the interaction with commercial and illegal fishing. In conclusion, the measures adopted have not been effective, given that the vaquita population continues to decline. There are failures in the application of regulations, insufficient monitoring and surveillance, unregistered captures, illegal fishing and the limited participation of human communities in the design and implementation of the regulations, perceiving damages and lack of interest in compliance with the regulations and proposed measures. Beyond the knowledge gained, research is needed to answer a key question: are current habitat and ecosystem conditions suitable for the vaquita population to recover? The answer to this question requires different and even currently non-existent knowledge.

KEYWORDS

vaquita, *Phocoena sinus*, Upper Gulf of California, conservation, endangered, illegal capture, Colorado river Delta

1 Introduction

The vaquita (*Phocoena sinus*, Norris and McFarland, 1958) is a marine mammal species belonging to the group of porpoises and is endemic to the Upper Gulf of California (UGC) region. According to the available information, the vaquita population has decreased monotonically in recent decades; the decline in its abundance (Ortega-Ortíz et al., 2000) is one of the greatest with respect to other species of both terrestrial and marine mammals and it is catalogued by the Convention on International Trade in Endangered Species of Wild Fauna and Flora, CITES (Appendix 1) as a species under imminent risk of extinction; by the International Union for the Conservation of the Nature, IUCN, as a species that is in critical danger (CR); and as a species that is in Danger of Extinction (P) by the official Mexican Standard NOM-059-SEMARNAT-2010. Concern about this condition at the national and international levels has led to various actions, both those of a technical-practical nature aimed at reversing its current condition, such as those designed to strengthen management to guarantee the success of conservation efforts. In both cases, it has been argued, with some degree of evidence, that the primary cause of vaquita mortality is bycatch during illegal totoaba (*Totoaba macdonaldii*, Berdegué, 1955) fishing, even though, for years, measures were adopted to avoid negative interactions (Vidal et al., 1994; Jefferson and Curry, 1994, D'agrosa et al., 1996).

Notably, it has been argued that the ecosystem and habitat of the vaquita have undergone changes that could be relevant to sustaining the population, including the historical reduction of flows from the Colorado River towards the UGC. These hydrographic changes caused the transition from estuarine to anti-estuarine conditions (Álvarez-Borrego, 2001; Zamora et al., 2013; Brusca et al., 2017) and, more recently, the effects of climate change, particularly since the 1980s in various parts of the world, including the Gulf of California, a change in the environmental regime manifested, as suggested by a time series of various environmental variables (Lluch-Belda et al., 1989; Steele, 1998; Bakun, 2004; Sheffer et al., 2001). In both cases, the central argument refers to possible indirect effects on the vaquita through changes in communities and habitat, which constitutes a relevant threat given that the species could have little genetic flexibility to adapt to such changes (Rosel et al., 1995; Ortega-Ortíz et al., 2000; Bhagarathi et al., 2024). However, although these arguments seem logical, there is no solid scientific evidence to support these hypotheses.

The relevance of knowledge about the dynamics of the vaquita's ecosystem and habitat lies in one question; that is, assuming a scenario without bycatch, are the ecosystem and habitat conditions adequate for the vaquita population to recover? Or what would be the opportunity for the vaquita population to recover if environmental conditions were not optimal or adequate? The relevant concept behind these questions is the lack of scientific knowledge about the role of the vaquita in the ecosystem, its habitat and the possible impacts of changes in the environment on its population. Obviously, addressing this approach requires, in the first instance, knowing the current state of scientific knowledge about the vaquita, what the analysis approaches are, and what the information gaps are. From this diagnosis, hypotheses or questions can then be formulated to guide future research. The objective of this contribution is to determine the state of scientific knowledge on the vaquita.

2 Materials and methods

The diagnosis on the state of knowledge about the vaquita (*P. sinus*) focuses particularly on peer-reviewed scientific literature. For this purpose, the following types of analysis were defined: bibliometric analysis and bibliographic analysis. The first consists of analyzing quantitative features of the scientific literature that allow for the identification of approaches, research trends, and consolidated, emerging or poorly addressed research areas. Second, bibliographic analysis seeks to synthesize the scope of the main findings of published scientific studies. Technical reports are not included in this analysis because although they contain relevant information, they still require the validation and formalization of scientific evidence.

2.1 Search and selection of bibliographic information

The search and selection procedure were based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method proposed by Liberati et al. (2009). This method is based on a systematic review of the literature with a structured methodology that facilitates replicating and updating the review as well as evaluating the reliability of the findings. Basically, it consists of discarding or including documents according to previously established eligibility criteria at each stage of the process.

A systematic search of the scientific literature related to vaquita studies was performed in October 2024. To this end, the bibliographic repositories Scopus (www.scopus.com), Dimensions (www.dimensions.com), Web of Clarivate Science analytics, WoS (www.webofscience.com) and JSTOR (www.jstor.org) were consulted. Initially, these search engines were used to obtain scientific works that contained the term "*Phocoena sinus*" or "vaquita" in the title or abstract of the document. Under these search criteria, more than 4,000 results were obtained. Of the four databases consulted, only WoS was chosen due to the consistency of the results since it is one of the scientific platforms with the best reputations (Bhardwaj, 2016; Li et al., 2018) and, more specifically, because it uses policies for the inclusion of scientific contributions that meet the criteria to be included in the Science Citation Index (SCI). In contrast, other repositories place greater emphasis on coverage and less emphasis on source selectivity (Visser et al., 2021). However, the different repositories are not necessarily mutually exclusive, so the use of WoS is convenient given the scientific connotations sought here.

Subsequently, the documents found in the WoS were manually filtered. Duplicate documents were eliminated, and the titles and abstracts of the resulting documents were read to ensure the relevance of the study. Scientific studies on the vaquita *Phocoena* *sinus* were established as inclusion criteria. In this way, studies on other species of the same genus *Phocoena* or that included only the word "vaquita" but did not refer to the species under study were excluded. After the information was filtered, 105 scientific documents focused on the vaquita *Phocoena sinus* were selected. These documents were verified, and capture errors in ASCII code in the fields of author names, titles and abstracts were corrected.

2.2 Bibliometric analysis

The bibliometric analysis was performed with the Bibliometrix version 4.1.3 package developed in the R programming language (Aria and Cuccurullo, 2017). For each year, the number of documents, authors, sources, document production rate, and citations per year were tallied. Additionally, different topics addressed in the literature on *P. sinus* and their trends over time were identified. This identification was based on the Keyword Plus (KP) generated by the WoS platform for each document included in its collection. KPs are words that frequently appear in the titles of references in a document but do not appear in the title of the document. The WoS platform creates these KPs with the purpose of increasing the visibility and relationship between documents based on the cited references. KPs were chosen instead of the keywords originally proposed by the authors because the percentage of documents containing KPs was greater.

The way in which the KPs changed over time was analyzed according to the approach proposed by Aria and Cuccurullo (2017) with the fieldByYear() function of the Biliometrix package. This function analyses the frequency of KPs and identifies the period in which most studies that include a specific KP are found, using the median and the first and third quartiles of the temporal distribution of the documents. The relationship between KPs was also analyzed using the approach proposed by Khasseh et al. (2017). These authors built a network model that relates the KPs to each other based on their frequency of joint appearance in the documents (co-occurrence). In this model, KPs are represented as nodes that are connected through links when they appear together in the same document. The more times two KPs appear together, the greater the weight of the connection between them. The "walktrap" community detection algorithm (Pons and Latapy, 2005) implemented in igraph for R (Csárdi and Nepusz, 2006) was used to detect sets of KPs that appear more intensely connected to each other than to other KPs within the net. This process allowed us to analyze the structure of the study topics in the scientific literature according to the similarity of the documents based on the KP.

2.3 Bibliographic analysis

Each of the selected publications was reviewed with the objective of synthesizing the advances and scope of scientific research on the vaquita. The information from each document was compared and synthesized, and trends and key topics in the field of research were identified. Emphasis was placed on two aspects: 1) the relative importance of the scientific topics addressed in the publications and 2) the identification of research areas according to the attention given to each one. This analysis allows us to identify the state of the art in the scientific knowledge on the vaquita and can be useful for designing future research based on the needs and priorities for generating knowledge.

3 Results

3.1 Bibliometric analysis

Table 1 shows the information used to analyze the scientific literature on the vaquita. Not all the documents had complete metadata. The keywords established by the authors had the lowest representation, which was compensated for by the Keyword Plus assigned by the WoS platform (Table 2).

Two periods were defined in the publication of articles on the vaquita: the first from 1993 to 1999 and the second from 2009 to 2021 (Figure 1). The origin of most of the authors is Mexico and the USA (Figure 2), while in half of the documents, there is at least one co-author from a country different from that of the other co-authors, including some from countries far from the region where the vaquita lives. This finding suggests important international efforts in scientific research on this species.

Figure 3 shows the researchers who have contributed the most scientific documents to knowledge about *Phocoena sinus*, the scientific journals in which the most information has been published on the subject, and the most cited works. Most of the sources in which the studies are published focus on topics relating to marine mammals or conservation, especially the magazine Marine Mammal Science, with an impact factor of 2.3 for the year 2022.

The most cited works are oriented towards factors that put the population at risk (bycatch, e.g., Rojas-Bracho et al., 2006; Brownell et al., 2019) and estimates of population sizes (e.g., Barlow et al., 1997; Gerrodette et al., 1995; Gerrodette et al., 2011, Jaramillo-Legorreta et al, 1999). The work on the management of fishing pressure (e.g., Ávila-Forcada et al., 2012), the impact of protected areas on the conservation of the species (e.g., Gerrodette and Rojas-Bracho, 2011), and the analysis of environmental policies aimed at the conservation of the species are common themes (e.g., Bobadilla et al., 2011).

The temporal analysis and frequency of the main KPs show the evolution of the topics addressed (Figure 4). The KPs that appeared

TABLE 1 Characteristics of the documents selected for bibliometric and bibliographic analysis on scientific knowledge about *Phocoena sinus*.

Period	January 1968 - October 2024
Number of documents	130
Number of authors	366
Number of sources	81
Annual growth rate (documents)	2.09
Average citations per document	27.32

TABLE 2 Representation of the metadata included in the documents selected for scientific literature review on *P. sinus*.

Metadata	Description	Documents missing	Percentage of representation
AB	Abstract	0	100
DT	Document type	0	100
SW	Fountain	0	100
P.Y.	Year of publication	0	100
YOU	Qualification	0	100
T.C.	Total Appointments	0	100
AU	Authors	1	99
IC	Author Affiliation	3	97
C.R.	References cited	32	69
OF	Keywords	48	54
ID	Keywords Plus (WoS)	32	70

to have the longest duration were "population", "conservation", "life history", "abundance" and "mortality". This trend reveals that studies regarding the vaquita population have been on the research agenda for long periods. The most frequent KPs were "fisheries", "conservation" and "life history". These terms suggest that studies that include the impact of fisheries and the conservation of the species have been frequently discussed in the literature. Additionally, KPs such as "mortality", "abundance", "bycatch", "endangered" species and "fisheries", which refer to the impact that fishing has on the vaquita population, have evolved such that in more recent years, the KP "extinction" appears to be a relevant and current issue.

Figure 5 shows the three KPs with the greatest relationships to the others: "conservation", "fisheries" and "population characteristics". KP sets that refer to biological and ecological studies such as "diet" and "ecosystem", "growth" and "age" were identified, or others that relate genetic characteristics and the vulnerability of the species such as "in-breeding", depression" and "endangered species". Other groups address issues such as the effects of fishing mortality. mortality ("by-catch" and "rare species") and some studies specialized in demographic estimates ("demography", "generations" and "effective population size"). However, the two most important groups of studies address conservation aspects and population characteristics. KPs such as "management", "bycatch", (population), "decline", "life history" and "fisheries" represent topics that are addressed in the set of topics related to conservation. The KPs representative of the population characteristics of the vaquita are "biology", "abundance", "genetics" "genome", and "mortality", among others. Almost half of the connections occur between different sets of KPs, which indicates that a considerable percentage of topics are addressed in an interdisciplinary manner.

The KP analyses, such as temporal trends and the co-occurrence network, tend to separate the content of the publications into two major scientific topics, namely population and conservation (Figure 5), while it is notable that among them, the greatest co-occurrence of concepts is also established, particularly fisheries and bycatch issues within the conservation context. In contrast, topics related to ecosystems and diets, which appear to be totally isolated, have drawn a great deal of attention, as has the absence of topics related to the effects of environmental changes and climate patterns. Next, the state of knowledge on the topics relevant to the study of the vaquita in the UGC is summarized.

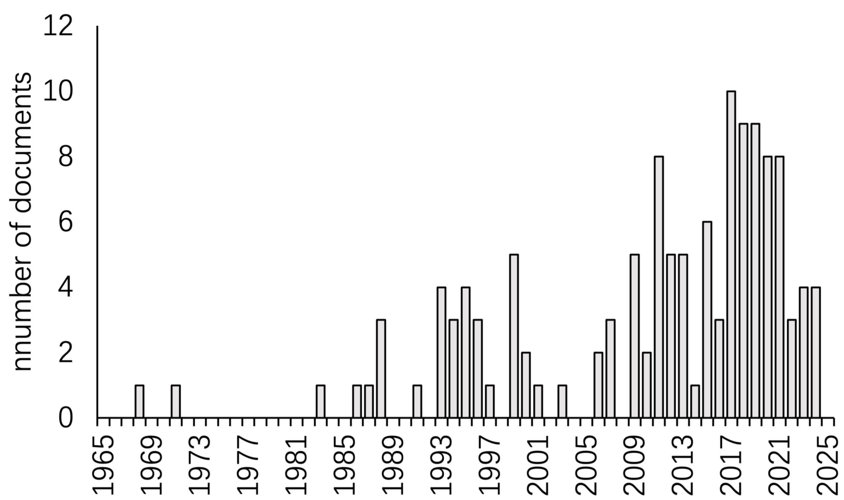

FIGURE 1
Total scientific production from 1968 to the October 2024 on *Phocoena sinus*.

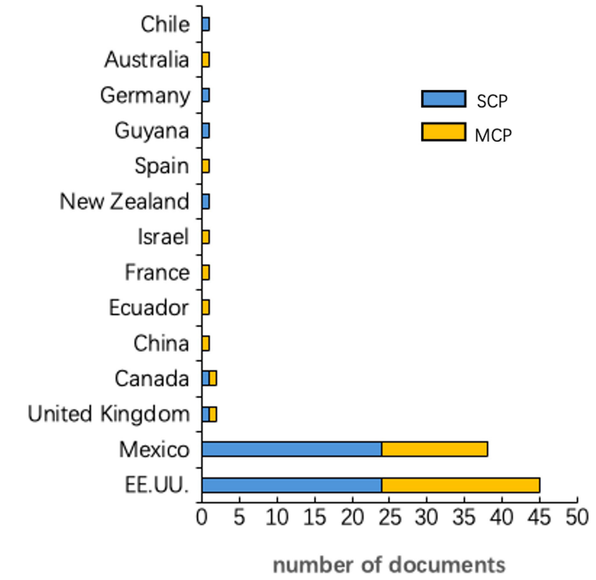

FIGURE 2
Number of scientific documents published by country. SCP: documents with authors from a single country; MCP: documents with at least one co-author from a different country, which is a measure of the degree of international collaboration.

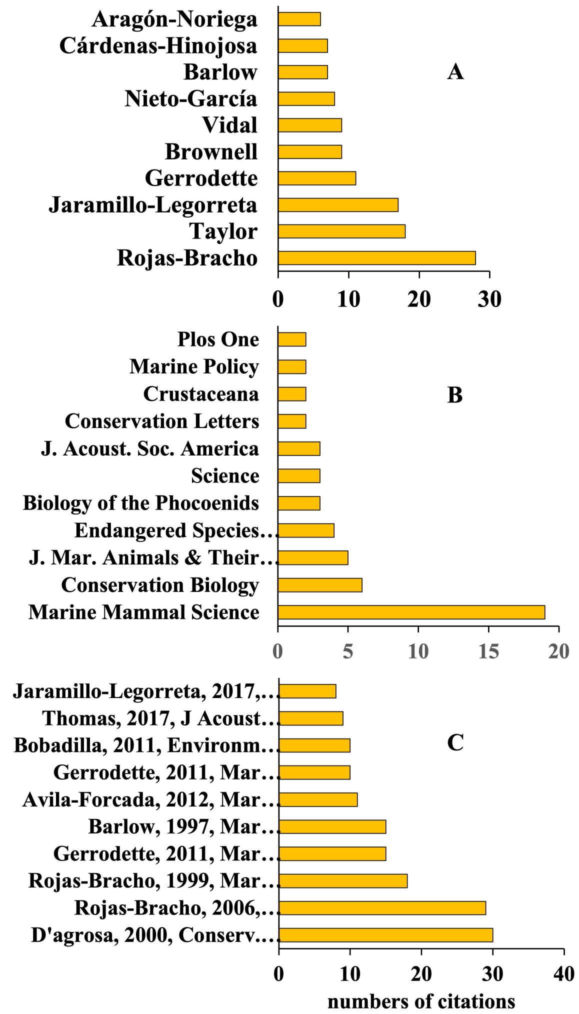

FIGURE 3
Authors with greater productivity **(A)**, and sources **(B)** with the greatest number of documents; and most cited scientific articles **(C)** in the collection. In all three cases, the 10 most relevant elements are shown.

3.2 Bibliographic analysis

3.2.1 Knowledge about the vaquita population

3.2.1.1 Population: biology and genetics

The species was described in 1958 from skeletons (Norris and McFarland, 1958). The first biological studies (osteological and feeding studies) (Fitch and Brownell Jr, 1968; Noble and Fraser, 1971; Brownell Jr., 1983; Brownell Jr. et al., 1987) were performed using equipment referred to as gillnets, using remains found on beaches and organisms captured incidentally. Shortly afterwards, Silber (1988) recorded the dynamics of the breathing and diving cycles; Lamothe-Argumedo (1988) described an intestinal parasite, and Pérez-Cortés et al. (1996) reported the stomach contents of 8 individuals, characterizing the diet of the vaquita. Despite this, in the 1970s and 1980s, publications were scarce. In 1993, the Biosphere Reserve of the Northern Gulf of California and the Colorado River Delta (BR) were declared (DOF, 1993). The Colorado River Delta region was established as the core of the BR and is a buffer zone that extends south to San Felipe (Baja California) and Puerto Peñasco (Sonora) (Figure 6). In 1997, the presence of 567 vaquitas was estimated to potentially have decreased annually by up to 40% if bycatch was not stopped (Rojas-Bracho et al., 2019). In 2005, the Refuge Zone for the Protection of the Vaquita Marina, ZR (DOF, 2005), was decreed, covering the area with the highest concentration of these organisms (Rodríguez-Pérez et al., 2023); however, part of such refuge is located outside the protected area of the BR, coinciding with fishing areas (Álvarez-Borrego, 2001; Rojas-Bracho and Jaramillo-Legorreta, 2009; Rodríguez-Quiroz et al., 2009; Aguilar-Maldonado et al., 2017). Likewise, it has been mentioned that the vaquita is a highly vulnerable and fragile species given its life history characteristics, such as its sexual maturity requiring up to 6 years and having a frequency of two-year births (Hohn et al., 1996); however, Taylor et al. (2019) mention that the vaquita can give birth annually, which is relevant for its potential recovery.

Analyses suggest that vaquita is a species with a low effective population size (Ne), which means that it is naturally rare (Rosel et al., 1995; Rosel, 1999). This condition made the species more sensitive to population reduction during late Pleistocene climate change in the North Pacific (Morin et al., 2021). The studies also agree on the emergence of mechanisms that favor the purging or elimination of recessive deleterious alleles, thus reducing the risk of inbreeding depression (Taylor and Rojas-Bracho, 1999; García-Dorado and Hedrick, 2023) and increasing tolerance to the consequences of bottlenecks (when genetic drift rapidly reduces genetic variability in small populations) (Munguia-Vega et al., 2007). Phylogenetic evidence indicates that the population is small, closed and interbred (Morin et al., 2021) and has maintained a low Ne for more than 5000 years (Chehida et al., 2020). The historical estimate of Ne is relatively greater than that of

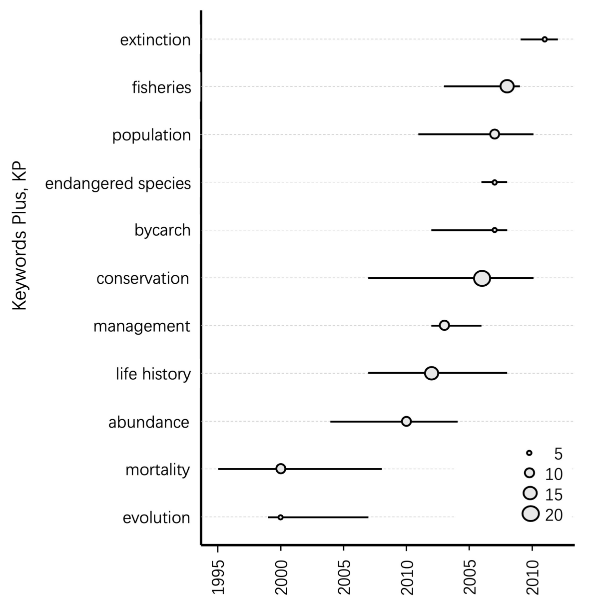

FIGURE 4
Temporal distribution of the main topics addressed in scientific research on *Phocoena sinus*. The Keywords Plus (KP) generated by the WoS platform associated with each document included in the analysis were used here. The temporal range shows the first and third quartiles of the temporal distribution. The point represents the median, and its size represents the frequency of the topic. Only KPs with a minimum frequency of five are shown.

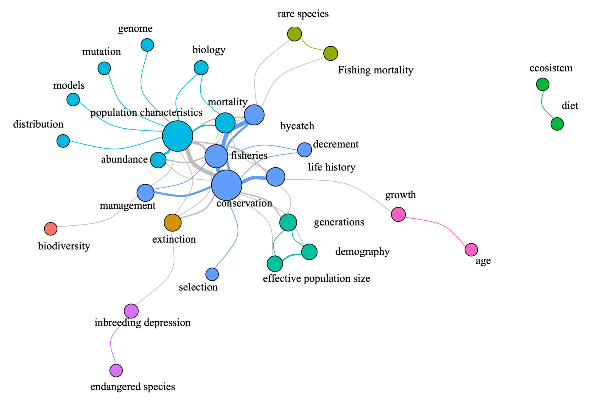

FIGURE 5
Keyword co-occurrence network (Keywords Plus, KP) in the documents analyzed for the *Phocoena sinus* bibliographic review. The colours of the connections and nodes represent the sets of KPs that are frequently associated. The lines represent the connections between different sets of KPs. The line thickness is proportional to the relationship level of each KP with others, and the size of the nodes are proportional to the number of connections of each KP.

mammalian species in critical condition (>50 individuals), which is why it has not been historically threatened (Morin et al., 2021; García-Dorado and Hedrick, 2023). Allele and polymorphism analyses have shown that the species has very low genetic variability, with variation of less than 0.01% (Rosel, 1999; Taylor and Rojas-Bracho, 1999; Munguia-Vega et al., 2007; Chehida et al., 2020).

Some studies hypothesize that low genetic diversity and inbreeding behavior may be due to a recent bottleneck. However, most evidence indicates that this event was not recent (Taylor and Rojas-Bracho, 1999; García-Dorado and Hedrick, 2023). Research based on simulations of population dynamics indicates that the decrease in mitochondrial DNA diversity is due to historical rarity or an origin with a small population (Chehida et al., 2020). Therefore, the hypothesis that this condition is a consequence of bycatch is not supported by genetic evidence (Rosel, 1999; Chehida et al., 2020). Robinson et al. (2022) indicated that inbreeding is not considered a threat factor for the permanence of the vaquita population; however, other authors (Morin et al., 2021; García-Dorado and Hedrick, 2023) have suggested that the dramatic decline of the population in a few generations could cause inbreeding to affect the few remaining individuals and contribute to their extinction. In this sense, Grueber and Sunnucks (2022) mention the possible use of genomic data to examine genetic diversity and anticipate potential effects on possible future population trends.

The vaquita presents “paedomorphic” ossification in the fins with an unusual formula in its phalanges, which could be the result of the genetic drift of a population with a small number of individuals (Ortega-Ortíz et al., 2000; Mellor et al., 2009). Similarly, the vaquita presents bone (Racicot and Colbert, 2013) and sexual dimorphisms between female and male vaquitas (Torre et al., 2014), probably due to their differences in behavior. Furthermore, the species presents polydactyly, which is a fixed trait present in both fins of 16 examined specimens (Ortega- Ortíz et al., 2000). Additionally, vertebral hyperosteitis has been reported in 23% of 62 specimens examined, and the fusion of vertebrae 26 and 27 through the neural spines in 55% of individuals with this malformation is considered a product of low genetic variability, which, according to experts, raises doubts about the degree of evolutionary flexibility in the species (Rosel et al., 1995; Taylor and Rojas-Bracho, 1999; Ortega-Ortíz et al., 2000). Phylogenetic and demographic studies suggest that the species is historically vulnerable to changes in habitat and environment and that it was restricted to the Northern Gulf of California (Rosel, 1999; Chehida et al., 2020) and that its habitat was probably reduced or eliminated due to the decrease in sea level on several occasions during the last 350,000 years (Morin et al., 2021).

3.2.1.2 Knowledge of the current habitat

Brownell (1986) reported the distribution of the vaquita in the UGC based on confirmed sighting records. Later, Silber et al. (1988) and Silber and Norris (1991) reported, also based on sightings of individual organisms and in groups, provided information on habitat use in shallow coastal areas. The vaquita lives on the western margin of the UGC, where the refuge zone of the species was decreed in 2005. This zone is characterized by depths of <30 m, proximity to the coast (<40 km) and gentle slopes (<0.001°), in addition to the presence of fine sediments rich in organic matter that were generated from the residual sediments of the Colorado River in the past. In this area, high values of chlorophyll and primary production are associated with dominant turbulence (Rojas-Bracho and Jaramillo-Legorreta, 2009; Carriquiry and Sánchez, 1999, Álvarez-Borrego, 2001, Brusca et al.,

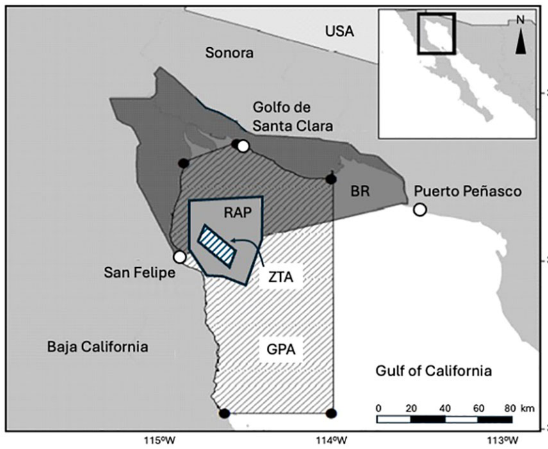

FIGURE 6
Distribution and protection area of the vaquita *Phocoena sinus*. BR = Upper Gulf of California and the Colorado River Delta Biosphere Reserve; ZN = core zone; ARP = refuge area for the protection of the vaquita; AT0 = zero tolerance area (no fishing); and APR = gillnet prohibition area.

2017; Aguilar-Maldonado et al., 2017). Likewise, relatively high values of $\delta^{15}N$ have been recorded in sediment and zooplankton as caused by the recycling of organic matter and upwelling by local winds (Rodríguez-Pérez et al., 2018; Ramírez-León et al., 2015; Aguilar-Maldonado et al., 2017; Brusca et al., 2017). It has been suggested that the presence of vaquita in turbid waters could reflect an ecological strategy to avoid predators (Rodríguez-Pérez et al., 2018). The vaquita's habitat has recently decreased in association with population reductions (Rodríguez-Pérez et al., 2023).

The contribution of the Colorado River flow to the UGC decreased significantly to practically zero after the construction of the Hoover and Glenn Canyon dams (Zamora et al., 2013). This reduction caused a change from estuarine conditions to anti-estuarine conditions (Álvarez-Borrego, 2001; Brusca et al., 2017). Some authors suggest that the decrease in the flow of the Colorado River has not affected the productivity of the region; for example, in analyzing 35 years of data, Ramírez-León et al. (2015) suggest that it is a healthy ecosystem, while Brusca et al. (2017) indicate that fertilization is determined by various factors, highlighting upwelling processes, also suggesting that the current fauna of the UGC is adapted to fluctuations in the contributions of the Colorado River and the increase in salinity. However, other authors suggest that the historical change towards hypersaline waters represents an alteration of the environment, particularly in the vaquita refuge area, where sediments were derived from the river (e.g., Lavín et al., 1998; Lavín and Sánchez, 1999; Santamaría-del-Ángel et al., 2017). This change seems to modify the structure of the communities, and changes may occur in the trophic relationships of various species, including the vaquita (Riofrío et al., 2013; Rodríguez-Pérez et al., 2018). Upon analyzing the trophic niche of the species through the $\delta^{13}C$ and $\delta^{15}N$ values in bone, it was found that the vaquita is a predatory organism with a high trophic level and a generalist nature, that there are no differences between sexes, and that the vaquita feeds on small benthic and pelagic organisms, prey that have changed in abundance and distribution (Rodríguez-Pérez et al., 2021), which can increase vaquita's vulnerability, especially because its limited distribution (Bhagarathi et al., 2024). Dolphin populations are direct competitors of vaquita, with a similar trophic niche (Riofrío et al., 2013; Cárdenas-Hinojosa et al., 2020), increasing stress on the vaquita population.

3.2.1.3 Effects of climate and environment

There is very little information regarding the possible effects of changing climate patterns on the vaquita; however, it has been suggested that the vaquita may be vulnerable to climate patterns and be negatively impacted by being confined to a small geographic area largely delimited by land, which limits the possibility of migrating to other latitudes as a potential response to changes in the environment (Simmonds and Isaac, 2007). The available records indicate that the species has the most restricted area of distribution (2235 km^2) (Munguia-Vega et al., 2007) of all species of marine cetaceans, which exhibit a relatively wide range of distribution on a global scale (Chehida et al., 2020). In contrast, statistically significant effects of climatic variables such as sea surface temperature, SST, the Pacific Decadal Oscillation, PDO, and the flow of the Colorado River, among others. These also affect some species that cohabit with the vaquita, such as the totoaba, corvinas (*Cynoscion* spp.), sharks (Selachimorpha), and rays (Batoidea) (Ruiz-Barreiro et al., 2019), some of which are common prey of the vaquitas (Riofrío-Lazo et al., 2013). Likewise, although it has been suggested that pollution could also be a cause of vaquita mortality, there are very few studies on this matter. Villa et al. (1993) reported the presence of heavy metals such as copper, cadmium, magnesium, iron, zinc and nickel; in addition to cobalt, lead and chromium in very low concentrations. These authors, however, report that the concentrations recorded are within the usual levels found in other marine mammals. On the other hand, Gulland et al. (2020) is the only formal study that mentions that pollution is not a cause of mortality, recording low concentrations of PCB, DDT and PBDE contaminants and the absence of saxifosine and domoic acid.

3.2.1.4 Ecosystem dynamics

A few studies have focused on assessing the state and effect of fisheries on ecosystems, exploring strategies that managers to combine the exploitation of resources and the conservation of biodiversity. There is no evidence of negative impacts of fishing on the functioning and organization of the ecosystem (e.g., Lercari and Arreguín-Sánchez, 2009; Del Monte-Luna et al., 2011; Riofrío-Lazo et al., 2013; Arreguín -Sánchez et al., 2017; Mendivil-Mendoza et al., 2018). Although none of these studies have focused on the vaquita, it has been suggested that predation, in addition to fishing, should be considered a key element in the dynamics of the vaquita population (Díaz-Uribe et al., 2012).

3.2.1.5 Population size

There is little information on the historical size of the vaquita population for the period before bycatch was identified as a factor in population decline (Würsig et al., 2021). Estimates in the 1980s show that the population was already small and already declining in abundance. Between 1986 and 1989, Silber et al. (1994) reported that vaquitas, along with Bryde's whales, had the smallest groups among cetaceans seen in the UGC area. Based on literature data, Vidal (1995) reported 68 vaquita records and identified 29 additional specimens. The first reliable and specific estimates of the population size were made between 1986 and 1993 using aerial and marine visual transects (Barlow et al., 1997). With this information, a population of 885 individuals was estimated between 1988-1989, and from sightings from larger boats, 224 individuals were recorded, which represents a population decline rate of 17.7% annually (Ortega-Ortíz et al., 2000).

In 1977, Jaramillo-Legorreta et al. (1999) reported 125 sightings of vaquitas and an estimated population size of 567 individuals (visual survey). In 2008, a population of 245 individuals was estimated through linear, visual and acoustic transects (Gerrodette et al., 2011), and the average rate of population decline was 7.6% per year starting in 1997. In both cases, the authors agreed that part of the vaquita population is located outside the limits of the UGC Biosphere Reserve, the Colorado River Delta and the Refuge Area for the Protection of the Vaquita. Fleischer et al. (1996) estimate mortality rates for vaquita and totoaba using experimental fishing data for the period from 1983 to 1993. From 682 sets on totoaba, they estimated a mortality of 0.0058 vaquitas/set, and 3.4 totoabas/set. From 632 sets on fish, sharks, and shrimp, they estimated 0.006 totoabas/set and 0 vaquitas. They suggest that the commercial legal coastal fishing is not causing the decline of the vaquita. In a similar context, Urrutia-Osorio et al. (2015) estimate a mortality rate of 0.000003151 vaquitas per fishing trip and suggest strengthening fishing limitations as an urgent and drastic measure to protect the vaquita, highlighting the collaboration of science, government and fishing communities. On the other hand, using acoustic sensors, Jaramillo-Legorreta et al. (2017) counted approximately 200 vaquita individuals at the beginning of the period from 2011 to 2015 and reported that the population decreased by 80%, while Wursig et al. (2021) estimate, for 2019, a rate of decrease of 50% per year, highlighting the need for drastic measures. Based on these estimates, to save the vaquita, there is an urgent need to ban the use of gillnets. Taylor et al. (2017) estimated that only 59 vaquitas remained in the fall of 2015, and Jaramillo-Legorreta et al. (2019) estimated a population of fewer than 19 individuals as of the summer of 2018. These same authors reported 10 dead vaquitas in nets between March 2016 and March 2019, suggesting a probable underestimation of the probability that there were individuals outside the refuge and protection areas given the reports by Gerrodette et al. (2011b). The most recent results reported findings between 7 and 15 individuals in 2019 and between 5 and 13 in 2021 (Rojas-Bracho et al., 2022), with the presence of offspring, and that all the observed organisms appeared healthy. Finally, Cisneros-Mata et al. (2021) analyzed the viability of vaquita recovery if threats are eliminated. These authors suggest that the vaquita has the potential to recover, even from extremely low numbers if current threats are eliminated, indicating that its long-term viability will depend on its genetic diversity, which so far remains healthy.

3.2.2 Knowledge on the conservation of the vaquita

3.2.2.1 Population decrease and management measures

Since the beginning of the 1990s (Vidal, 1993) and to this date, the vaquita has been on the verge of extinction, with a population composed of fewer than 20 individuals in 2022. This species inhabits an ecosystem where human activities often clash with conservation efforts. Since 1975, the totoaba has been officially declared as an endangered species (a fishing moratorium was imposed on the fishery in the UGC) and in 1996, the vaquita entered the Red List as a "critically endangered" species. Brownell (1978) highlights the status of the vaquita population, pointing out direct threats (mortality caused by some fishing gear), aspects associated with the illegal trade of totoaba and changes in the flow of the Colorado River; mentioning some possible conservation measures.

The International Committee for the Recovery of the Vaquita (CIRVA) was established in 1993 in response to the continuous decline of the vaquita population despite the ban on totoaba fishing. Given the ineffectiveness of previous conservation measures, CIRVA proposed providing economic incentives to individuals who agreed to stop fishing, as a complementary measure to the moratorium on totoaba and trawl fishing in the upper Gulf. By the end of the 1990s, the Mexican government: 1) decreed the upper Gulf as a natural reserve (1993); 2) designed the management plan for vaquita and totoaba (1995); and 3) recognized that bycatch in gillnets and the increase of illegal fishing were the main threats to the vaquita (Vidal, 1993; Vidal et al., 1994; Jefferson and Curry, 1994; D'agrosa et al., 1996). The genetic deterioration of the population, pollution and the interruption of the flow of the Colorado River were also identified as factors that negatively affect the vaquita (Rojas-Bracho and Taylor, 1999). At that time, the vaquita population was estimated around 600 individuals, and 250 in 2008 (Jaramillo-Legorreta et al., 1999; Dalton, 2010).

Nearly ten years later, another conservation initiative was launched: The Action Program for the Conservation of the Vaquita Marina Species (PACE-Vaquita). Its primary objective was to provide economic incentives to fishermen to either temporarily or permanently stop fishing, or to switch to using safer fishing gear, all with the aim of conserving a population of 245 vaquitas. Avilla-Forcada et al. (2012) reported that five years after the initiative was implemented, individuals with alternative livelihoods voluntarily abandoned fishing activities, and those who switched to safer gears had the least productive fishing boats. By 2016, however, the vaquita population decreased 75% (Thomas et al., 2017).

Bobadilla et al. (2011) and Rojas-Bracho and Reeves (2013) present several reasons to explain why the PACE-Vaquita plan did not achieve its intended results: 1) a lack of methods to measure conservation success, 2) failure to communicate the negative impacts of fishing to fishermen, 3) insufficient interest among fishermen to participate in and respond to conservation initiatives, 4) the proposal of competing hypotheses that lacked a robust body of evidence compared to that concerning fishing mortality, and 5) a conflict between conservation and fishing goals, along with 6) inadequate surveillance of illegal fishing (Bobadilla et al., 2011; Rojas-Bracho and Reeves, 2013). In this context, several authors highlight that this is a very small population, in critical condition, and that management measures to date have been inefficient; pointing out the importance of increasing public awareness to address the inherent uncertainties (i.e. bycatch, discharge from the Colorado River) for which international collaboration is highly relevant (Jaramillo-Legorreta et al., 2007; Jefferson, 2008a, b, 2015; Bodeo and Whiteenfury, 2015; Cantú-Guzmán et al., 2015).

The reasons stated above, however, do not encompass all the angles from which the problem has been analyzed. In fact, there are studies that reach diametrically different conclusions. For example, Vázquez-León and Fermán-Almada (2010) stated that the objectives of the PACE-Vaquita do not include metrics for compliance or socioeconomic considerations. Rodríguez-Quiroz et al. (2018) argue that the PACE-Vaquita also fails to propose alternative solutions, and as a result, the implementation of such measures has not yielded any real benefits for fishermen. On the contrary: the local community remains unhappy and lacks motivation to support conservation efforts (Torres et al., 2018). By using ecosystem models, some authors argued that benefits for fishermen can adversely affect the vaquita, while measures aimed at supporting the vaquita can lead to decreased fishing yields and diminished social well-being (Lercari and Arreguín-Sánchez, 2009; Morzaria-Luna et al., 2013; Riofrío-Lazo et al., 2013; Arreguín-Sánchez et al., 2017).

CIRVA's latest initiative aimed to capture a small group of vaquitas from their natural habitat for placement in a protected environment. However, this mission, whose goal was safeguarding the species and ultimately releasing them into a habitat free of nets (Goldfarb, 2016; Rojas-Bracho et al., 2019), ended abruptly. They did capture a juvenile and an adult female; the former exhibited significant stress and had to be released, and the latter died shortly after capture (Pennisi, 2017). As of 2018, estimates indicated that fewer than 19 vaquitas were left in the upper Gulf of California. A new census (https://seashepherd.org/2024/06/11/executive_summary/) suggests that the vaquita population in 2024, may now be between 6 and 8 individuals, with a slight possibility that it could range from 9 to 11, which is lower than the previous estimate of 8 to 13 individuals in 2023.

3.2.2.2 Illegal and commercial fishing

In general, mortality from bycatch, primarily from gillnets, is considered to be the most important risk to the vaquita population (Rojas-Bracho and Taylor, 1999; D'agrosa et al., 2000; Rojas-Bracho et al., 2006; Reeves, 2009; Rodríguez-Quiroz, 2019); small-scale shrimp fishing and the illegal capture of totoaba (which uses gillnets) are also mentioned (e.g., D'agrosa et al., 2000; Flessa et al., 2019; Rojas-Bracho et al., 2022). In response, various management measures have been developed and implemented to reduce vaquita interactions with fishing gear, and they have been applied to legal fisheries (e.g., D'agrosa et al., 2000; Rojas-Bracho et al., 2006; Aburto-Oropeza et al., 2018).

In addition to the creation of the BR, other measures stand out, such as the prohibition of industrial shrimp fishing (Morzaria -Luna et al., 2013), the prohibition of the use of drift nets (Morzaria-Luna et al., 2012), the purchase of fishing permits to encourage the development of alternative activities (Rodríguez-Quiroz et al., 2009; Senko et al., 2014), economic compensation for stopping fishing during certain periods or with certain fishing gear (Ávila-Forcada et al., 2012; Torres et al., 2018; Rodríguez-Quiroz, 2019) and the development of new fishing gear that reduces the probability of incidentally capturing the vaquita (Senko et al., 2014; Aburto-Oropeza et al., 2018).

Among the challenges for the effective implementation of these management measures, it is worth highlighting that the UGC area is possibly the most important region for small-scale fishing in the country, with an estimated approximately 1000 vessels from three communities (the Gulf of Santa Clara, Puerto Peñasco and San Felipe) that take advantage of economically important resources such as blue shrimp, olive ridley croaker, northern milkfish and the Gulf sierra (Aragón-Noriega et al., 2009; Ruelas-Peña et al., 2012; Erisman et al., 2015; Mendivil-Mendoza et al., 2018). All these fisheries overlap with protected areas; for example, historically, the conventional capture area for blue shrimp comprises 99% of the refuge area surface. However, measures to control fishing have not had the expected success. Among the possible reasons for this failure is the lack of employment alternatives for the community, with an estimate that 23% of fishermen are not willing to leave the activity regardless of government strategies. Likewise, in the design of the management measures, the differences in the dynamics of the economy of each community were not considered, wasting local knowledge that causes fishermen to feel alienated by the objectives of said measures (Aragón-Noriega et al., 2010; Erisman et al., 2015; Cisneros-Montemayor and Vincent, 2016; Aburto-Oropeza et al., 2018; Rodríguez-Quiroz, 2019; Avila-Forcada et al., 2020).

Other reasons that put the vaquita at risk include situations that are difficult to foresee. For example, the ban on industrial shrimp fishing generated an incentive to increase small-scale fishing efforts in the area (Rodríguez-Quiroz et al., 2009). The modified fishing gear is less efficient than the traditional gear, which generates greater bycatch and has lower economic performance, in which the losses are not compensated by economic support (García-Gómez and Chávez-Nungaray, 2017; Aburto-Oropeza et al. al., 2018). Furthermore, compensation has not been formally recognized, which has generated economic conflicts in these communities (Morzaria-Luna et al., 2012; Torres et al., 2018) that are enhanced by the illegal capture of totoaba (Alvarado-Martínez and Martínez, 2018; Bonada-Chavarría, 2020; Aceves-Bueno et al., 2023). The extraction and international trade of the totoaba crop are coordinated by organized crime, which operates with relative ease, and in case of arrest, the penalties are relatively low (Alvarado-Martínez and Martínez, 2018; Chavarría, 2020). This activity not only puts the totoaba at risk but also is currently considered the main cause of vaquita mortality (Aceves-Bueno et al., 2023; Chavarría, 2020). This situation has also impacted legal fishermen since the decrease in the number of vaquitas has led to more restrictive management measures for them, without stopping the illegal capture of totoaba (Manjarrez-Bringas et al., 2018; Parsons, 2018). In parallel with the illegal capture of totoaba, vaquita mortality has been reported due to ghost fishing (primarily from lost gillnets), which can cause megafaunal mortality for more than three years. Thus, for example, from 2016 to 2018, 1,309 pieces of fishing gear were removed from vaquita habitats, and entangled turtles, sea lions, dolphins, and whales were reported during these cleaning campaigns (Aceves-Bueno et al., 2023).

In addition to illegal totoaba fishing, the lack of socialization of the management strategies and the lack of work alternatives in fishing communities have played a relevant role in reducing the effectiveness of measures to recover the totoaba and vaquita populations have not been successful (Rojas-Bracho et al., 2006; Bobadilla et al., 2011; Rojas-Bracho and Reeves, 2013; Sanjurjo-Rivera et al., 2021). In this sense, the effective application of these measures by the government and the consideration of the socioeconomic needs of coastal communities are considered relevant (von Fersen et al., 2024). For this purpose, instruments based on incentives are needed, in addition to the participation of the communities themselves in the search for solutions (Vázquez-León and Almada, 2010; Quiroz et al., 2019; Sanjurjo-Rivera et al., 2021; Aceves-Bueno et al., 2021). In the same direction, Smith et al. (2023) and Oyanedel et al. (2024) suggest that monitoring and controlling the trade of swim bladders can be an essential element to determine actions that could result in greater conservation effectiveness.

4 Discussion

To analyze the current state of knowledge about the vaquita, an intense bibliographic search was performed, and it was guided by a systematic and reproducible method. Of the bibliographic repositories explored here, the WoS provided greater scientific consistency, allowing for the classification or filtering of information across sources, especially based on criteria included in the Science Citation Index. This approach is relevant because it offers a recognized standard of analysis and scientific consistency (Bhardwaj, 2016; Li et al., 2018). From the bibliometric analysis, a KP co-occurrence network was obtained that illustrates the topics to which more attention has been given. The association between topics also stands out, which reveals the intensity of the relationship between them and, in some ways, the orientation of the use of scientific knowledge. Two major topics predominated, namely those related to population characteristics and those related to conservation. The rest of the themes, as shown in Figure 5, appeared to be linked with lower intensity but were clearly associated with the predominant topics. Similarly, themes such as ecosystem and diet appeared unrelated to the others. The absence of KP related to topics such as environment, climate and habitat is also noteworthy.

From the previous analysis, two topics that guide scientific research on the vaquita were clearly highlighted: those that refer to the population level and those that are oriented towards conservation and human intervention. From this finding, the bibliographic analysis of the scientific literature was organized. In both cases, from this perspective, inevitable mention is made of the creation of the BR, as well as the ARP, both in relation to the decreasing trend in the population. In addition to these topics, the biology of the species and its high vulnerability are mentioned, not only due to the low number of individuals but also due to the advanced age of sexual maturity (6 years) and low frequency of births. To explain this result, hypotheses have been explored in the literature about the risks of inbreeding combined with low genetic drift and the low number of individuals, which could trigger the bottleneck phenomenon.

There is currently information on the physical habitat of the vaquita, including specific data on its diet; however, key aspects of habitat suitability and utilization are unknown, and there is virtually no information on the possible effects of historical changes from original estuarine conditions to current anti-estuarine conditions or on possible effects on the environment or habitat due to changes in weather patterns. Together with the lack of knowledge about the habitat suitability, the lack of information about reproductive biology creates a context of uncertainty about the success of recovery. This knowledge is highly relevant in terms of the vulnerability, adaptability and resilience of the vaquita, which is key information in terms of the expected response to management and conservation actions.

With respect to the conservation of the species, the monotonic decline of the population is worrying (Figure 7), with an estimated 12.35% reduction from 885 individuals in 1990, for a current survival of less than 20 individuals.

Despite the conservation efforts, the expected results have not been achieved, and the debate continues about the possible causes of the decrease in the number of vaquitas, even though incidental fishing associated with illegal totoaba fishing has been noted as the main cause. The small population size of the vaquita forces a series of actions to be performed to avoid mortality due to bycatch in both legal and illegal fishing, actions that, in general, have been clearly defined and whose success depends largely on the efficiency of their implementation. However, as mentioned at the beginning,

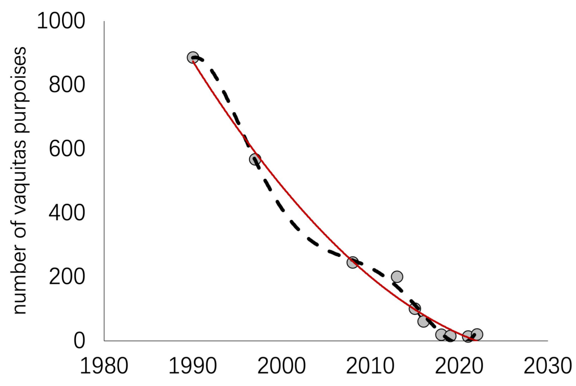

FIGURE 7
Historical decrease in the vaquita population of the Upper Gulf of California. The number of vaquitas represented by the points corresponds to the observed data. The solid line shows the fit to a linear model with an annual decrease rate of 12.35%. The dashed line shows partial trends in historical changes related to population decline. Note that the decrease in the mortality rate in approximately 2010 coincides with the implementation of the ARP for the protection of the vaquita and the PACE-Vaquita. In approximately 2015, the rate of population decline increased again, which is suggested to be associated with the increased illegal capture of totoaba.

assuming that these protection actions are implemented efficiently, the initial questions remain valid; that is, are the current ecosystem and habitat conditions suitable for the vaquita population to recover? This question establishes the need to determine the role of habitat disturbance in the possible restoration of the species and the current state of the ecosystem, as well as to recognize that key knowledge is missing to achieve the intended conservation and recovery of the vaquita.

Regarding conservation, it is evident that the focus of this research has been the high rate of population decline in recent decades. The studies have focused on four aspects, namely 1) the creation of protection areas and conservation programs, 2) monitoring of the remaining vaquita population and the low or no efficiency of the controls associated with bycatch due to illegal capture, 3) associated alternative measures (including little or no participation of the communities) and 4) effective conversion of fishing gear (including both technical aspects and economic performance). The global diagnosis highlights the absence of methodologies for the generation of indicators that allow for the measurement of the efficiency, monitoring and improvement of the different conservation actions. This knowledge would allow us to adapt and adjust these actions and promote their greater efficiency over time. However, it is worth highlighting the importance of having knowledge about the suitability of the habitat and the state of the ecosystem to be able to estimate the recovery goals in accordance with current conditions, considering dynamic sustainability; that is, the continuous reconfiguration of the ecosystem generated by the trends in environmental and climatic dynamics. In addition, Aceves-Bueno et al. (2021) and Oyadenel et al. (2024) highlight that illegal trade, throughout the value chain, accelerates vaquita mortality. It is recognized that fishermen are motivated by economic incentives, by pressure from cartels and social norms, intermediaries and sellers motivated by high returns from illegal operations, and consumers motivated by health benefits and social status associated with the consumption of totoaba swim bladders. It is suggested that mechanisms be sought to discourage and reduce the effects of previous practices, highlighting the need to generate viable and realistic alternatives for fishermen, promote alternative activities such as tourism or totoaba aquaculture, improve the capacities of the links in the value chain and regulations to discourage illegal activities. Due to the magnitude of this entire process, the importance of interdisciplinary decision-making is noted, with the participation of fishing communities and international collaboration.

In contrast, little scientific knowledge has been generated about the dynamics of the ecosystem, including the habitat, trophic niche, climate, environment and use. Why investigate this? Natural ecosystems are dynamic and sometimes have relatively stable periods. Natural and induced changes with a trend in the environment, both natural and induced ones, provoke responses in individuals (e.g., metabolism and robustness, which are often not identifiable in real time or in the short term) or in the population (e.g., reproductive success, and its persistence), and in the ecosystem (the continuous reconfiguration of the organization and functioning through interspecific relationships), which in many cases require time to manifest. Considering that the population is not an entity that is isolated from its environment and that it is not necessarily stable, it is assumed that the changes observed in the UGC triggered this process. The study of these changes and their effects will allow us to identify, in the case of the vaquita, its vulnerability, its potential persistence, and its resilience, which is assumed to be critical information for the design of conservation measures and potential recovery of the population.

5 Recommendations

There are several lines of research that were not detected in the present analysis that could support the recovery of the vaquita (for example, the analysis of the international trade of the totoaba crop, the dynamics of the illegal fleet, and recent analyses of environmental DNA). Within the evaluation of the changes in the habitat and ecosystems and their capacity to support the vaquita population, three lines of research are identified as priorities because of the effective implementation of conservation measures:

i) Changes in the habitat of the vaquita. This topic includes, and to the extent the information allows for evaluating the changes in the vaquita's habitat over time and identifies, as much as possible, the habitat suitability, current conditions and perspectives, given the hypothesis of the instability of the environment. This topic includes the areas of ecosystem dynamics, physical environment, climate patterns and environmental variability, trophic relationships, and the participation of fisheries, both directly (e.g., as bycatch) and indirectly (through the capture of species trophically associated with the vaquita).

ii) Assuming the absence of bycatch and illegal capture, it is considered relevant to answer the question of whether the conditions and dynamics of the ecosystem and habitat are adequate for the vaquita population to recover. In other words, what is the opportunity for the vaquita population to recover if the ecosystem, habitat and environmental conditions are not optimal or adequate? The answer to these questions should generate knowledge that allows for the exploration of the factors linked to the vulnerability, persistence (viability), adaptability and resilience of the vaquita population in greater detail. This response will also shed light on how efficient management measures can be for its conservation and recovery. In this context, it is essential to maintain direct and close communication and participation with communities that depend on UGC ecosystems.

iii) Generating knowledge about the effects of reducing drift and genetic variability and the potential risk of this so-called bottleneck.

Author contributions

FA-S: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MJZR: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. FV-S: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. PD-L: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. MR-F: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. GA-R: Formal analysis, Investigation, Writing – original draft. DM-C: Formal analysis, Investigation, Writing – original draft. LS-V: Formal analysis, Investigation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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