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Authors
Ramirez-Valdez, Arturo
Rowell, Timothy J
Dale, Katherine E
et al.

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Asymmetry across international borders: Research, fishery and management trends and economic value of the giant sea bass (*Stereolepis gigas*)

Arturo Ramírez-Valdez[1,2,3] | Timothy J. Rowell[4] | Katherine E. Dale[5] | Matthew T. Craig[6] | Larry G. Allen[7] | Juan Carlos Villaseñor-Derbez[2,8] | Andrés M. Cisneros-Montemayor[9] | Arturo Hernández-Velasco[2,10] | Jorge Torre[10] | Jennifer Hofmeister[11] | Brad E. Erisman[6]

[1]Marine Biology Research Division, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

[2]Giant Sea Bass Project - Proyecto Mero Gigante, Ensenada, Baja California, Mexico

[3]Facultad de Ciencias Marinas, Universidad Autónoma de Baja California, Ensenada, Baja California, Mexico

[4]Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Woods Hole, MA, USA

[5]University of California Santa Cruz, Santa Cruz, CA, USA

[6]Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, La Jolla, CA, USA

[7]Department of Biology, California State University, Northridge, CA, USA

[8]Bren School of Environmental Science & Management, University of California Santa Barbara, Santa Barbara, CA, USA

[9]Nippon Foundation Ocean Nexus Program, School of Resource and Environmental Management, Simon Fraser University, Vancouver, British Columbia, Canada

[10]Comunidad y Biodiversidad A.C., Guaymas, Sonora, Mexico

[11]California Department of Fish and Wildlife, San Diego, California, USA

Correspondence
Arturo Ramírez-Valdez, Marine Biology Research Division, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92037, USA.
Email: arturorv@ucsd.edu

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Abstract

Co-operation in the management of shared fish stocks is often necessary to achieve sustainability and reduce uncertainty. The United States of America (USA) and Mexico share a number of fish stocks and marine ecosystems, while there is some binational co-operation in scientific research, unilateral management decisions are generally the rule. We present a case study using the giant sea bass (*Stereolepis gigas*, Polyprionidae) to highlight how these management and research asymmetries can skew national perceptions of population status for a fully transboundary species. Scientific publications and annual funding related to giant sea bass are 7x and 25x higher in the USA, respectively, despite the fact that 73% of the species' range occurs in Mexico. Conversely, annual fishery production and consumptive value of giant sea bass in Mexico are 19x and 3.5x higher than in the USA, respectively, while the non-consumptive value related to dive ecotourism is 76x higher in the USA. These asymmetries have generated a distorted view of the population status of the giant sea bass across its entire range. This and other factors related to historical fishery dynamics and policy must be accounted for when assessing population status, and subsequent appropriate management responses, across geopolitical boundaries.

KEYWORDS
Binational collaboration, endangered species, fishery management, shared stocks, small-scale fisheries, transboundary fisheries

1 | INTRODUCTION

Geopolitical boundaries can be problematic for conservation and management, often manifested by asymmetries in research efforts, publication of results, management outcomes, taxonomic decisions and economic revenues for both terrestrial and aquatic systems (Craig et al., 2009; Munro, 1990; Song et al., 2017). For example, differences in research effort across political borders can trigger differences in the amount of published information, which, in turn, may impact the perception of the status of marine resources on either side of a boundary (Miller & Munro, 2002; Schreiber & Halliday, 2013; Soomai, 2017). Similarly, asymmetric management of marine resources can threaten fish populations through overfishing, generate economic disparities and compromise neighbouring populations by perturbing source-sink dynamics. Conversely, co-ordinated management of connected populations may allow for the replenishment of depleted stocks, enhance population resilience and maintain genetic diversity (Munro, 2018; Palacios-Abrantes et al., 2020; Pinsky et al., 2018). Differences in the research and management of shared resources between nations are driven by a variety of factors including perceptions of the importance of a resource, economic and social disparities, management priorities and resources available for research and management (Hanich et al., 2015; Scholtens & Bavinck, 2014).

Co-operative management of shared fish stocks is often necessary to achieve sustainability and to reduce uncertainty in predictions of stock conditions (Cisneros-Montemayor et al., 2020; Ishimura et al., 2013; Pinsky et al., 2018). Challenges to the effective management of transboundary fishery resources may be exacerbated by climate change and other environmental stressors that underscore the need to emphasize co-operative approaches for long-term sustainability (Free et al., 2020; Gaines et al., 2018; Maureaud et al., 2020; Miller et al., 2013). Despite the fact that as many as 693 demersal and 194 pelagic marine fish and invertebrate species worldwide are managed within more than one Exclusive Economic Zone (EEZ), very few are co-operatively managed (Caddy, 1997; Palacios-Abrantes et al., 2020; Pinsky et al., 2018). The United Nations Convention on the Law of the Sea (UNCLOS, 1982) grants each country exclusive rights to set its own goals in the management and evaluation of resources within its EEZs. However, such goals are typically created independently from neighbouring states even though UNCLOS holds that nations must ensure that the fisheries within their EEZ are not overexploited and co-operate with neighbour states to establish adequate management measures for shared resources. Thus, social and economic contexts often shape management strategies that are seemingly out of sync with those of neighbours sharing ecosystems and stocks (Lane & Stephenson, 1995; Miller & Munro, 2004). Nevertheless, a growing body of literature provides tools for navigating the complexities associated with the management of transboundary stocks (Caddy, 1997; Molenaar & Caddell, 2019; Munro, 1979).

Even though the marine region off the coast of California (USA) and Baja California (Mexico) is considered a single marine biogeographic unit (Horn et al., 2006; Ramírez-Valdez et al., 2015), transboundary management of shared fish stocks is complicated by environmental complexity, higher-level differences in research infrastructure, social needs, economics and environmental policies (Cisneros-Montemayor et al., 2020). Generally, marine species in the region maintain genetic connectivity and utilize similar critical habitats on both sides of the US-Mexico border, highlighting the need for co-operative management of shared fish stocks (Aalbers et al., 2021; Block et al., 2011; Gaffney et al., 2007; Munguía-Vega et al., 2015). In 2020, the USA, Mexico and Canada signed a trade agreement that includes provisions for preventing overfishing, reducing incidental catch, promoting the recovery of overfished stocks and protecting marine habitat (US-Mexico-Canada Agreement Implementation Act:

USMCA, 2019). Additionally, state-level regulations in both countries recognize the potential contribution of populations to the other country, encourage regional approaches to marine management and emphasize co-ordinated approaches to the management of shared fisheries (Baja California's Fishery Agency, 2018; Leet et al., 2001). Despite this clear environmental and economic justification for co-management, legal frameworks encouraging it, and a rich history of collaboration between scientists in Mexico and California, no species are co-managed in this region.

An emblematic case of a species whose co-management is warranted is the giant sea bass (*Stereolepis gigas*, Polyprionidae, hereafter GSB). Currently, classified as Critically Endangered by the IUCN due to overfishing, GSB is distributed from Humboldt Bay in northern California to the tip of the Baja California peninsula, including the entire Gulf of California (Cornish, 2004; Domeier, 2001). The GSB is the largest coastal bony fish in the North-eastern Pacific, growing up to 2.7 m in total length and weighing up to 255 kg (Allen, 2017; Allen & Andrews, 2012; Domeier, 2001). This species is a top predator that preys on a wide range of fish and macroinvertebrate species and was once plentiful within the rocky reefs and kelp forests of California and Baja California (Burns et al., 2020; Chabot et al., 2015; Gaffney et al., 2007; Horn & Ferry-Graham, 2006; Tegner & Dayton, 2000; Vilalta-Navas et al., 2018). Several life history traits make GSB particularly susceptible to overfishing, including a slow growth rate ($k = 0.05$), long lifespan (76 years), late onset of sexual maturity (11–13 years) and the propensity to form spawning aggregations at specific locations from July to November (Clark & Allen, 2018; Domeier, 2001; Hawk & Allen, 2014; House et al., 2016). These same factors partially explain the slow rate of population recovery following protection from fishing (Clark & Allen, 2018; Pondella & Allen, 2008).

Following severe fishery and population declines of GSB in California, strong conservation regulations were incrementally imposed in US waters. While regulations in Mexico have remained nearly non-existent (Table 1) (Allen, 2017; Domeier, 2001; Pondella & Allen, 2008). In 1981, a ban on commercial and recreational GSB fishing was passed in the USA, but the California population continues to be well below historical levels (Baldwin & Keiser, 2008; Dayton et al., 1998; House et al., 2016; Ragen, 1990). Currently, GSB is protected as a no-take species in California to facilitate continual population recovery, but commercial fishers are still permitted to land one incidental catch per trip, and the species has not been granted federal protections under the US Endangered Species Act (Musick et al., 2000). While GSB is no longer targeted by fisheries in California, its gradual recovery has supported a multi-million-dollar industry associated with non-extractive recreational activities, such as SCUBA diving (Guerra et al., 2017) and public aquariums (National Ocean Economics Program, 2021). Conversely in Mexico, there are no regulations in place for the Mexican commercial fishery, and there is a dearth of information about the past and current status of the stock to inform future management (DOF, 2006). GSB remains an important fishery resource in Mexico, where small-scale commercial fishing communities continue to have a strong connection with this resource due to local traditions, and recreational fishers can land one fish per day.

Given the disparities in the use, knowledge and regulation of this shared resource coupled with a need for co-management, there is an urgency to further understand the trends and effects of past and contemporary fisheries and regulations on GSB stocks in the USA and Mexico and identify factors that present challenges for the management, conservation and sustainability of the species. In this study, we analysed disparities between the USA and Mexico for GSB related to: (i) scientific research efforts; (ii) fishery and management trends; (iii) spatial patterns of the contemporary fishery (2000–2016) and (iv) consumptive and non-consumptive economic value. This work represents the first study to incorporate historical and contemporary perspectives of the GSB fishery throughout its entire geographic range and reveals how asymmetries in the use, knowledge, and regulation of GSB may influence the perception of the species status in the USA and Mexico.

2 | MATERIALS AND METHODS

2.1 | Asymmetry in scientific research

We assessed the investment in scientific research on GSB by conducting systematic literature reviews on ISI Web of Science and Google Scholar that used the following search terms: "*Stereolepis gigas*," "giant sea bass," "black sea bass" + *Stereolepis*, "mero gigante," and "pescara" (Table 2); the latter two terms refer to the common names of GSB in Spanish (Page et al., 2013). In addition, we cross-checked the reference lists contained within all peer-reviewed articles focussed on GSB. We downloaded and reviewed every article to filter those that mentioned GSB as part of the references or species lists. The main topic, year of publication and the locations of the populations studied were extracted from each article. We then compiled this information to summarize what is known about the life history, ecology, genetics, fishery and conservation of GSB (Table S1). In addition, we incorporated data on GSB described in book chapters and grey literature resources identified and cited within such articles. We also combined information from the literature review and data extracted from the Global Biodiversity Information Facility (https://www.gbif.org), California Department of Fish and Wildlife (CDFW), the California Recreational Fisheries Survey (CRFS; https://www.recfin.org/), the Mexican government fisheries and aquaculture management agency (CONAPESCA), scientific collections in Mexico and the USA, fishery-dependent data and fishery-independent surveys to develop a species distribution map for GSB.

We summarized research efforts on GSB by compiling an exhaustive list of institutions and organizations from both countries that have been involved in GSB initiatives and requested information on project locations, total research funding and project durations. Organizations included research groups within academic institutions, non-governmental organizations, government agencies, aquariums and independent specialists. As some respondents reported total research funding over the duration of multi-year projects, grant funds were divided by years of project durations to

TABLE 1 Management policies, conservation categorizations and government regulations that impacted in the giant sea bass (GSB) management across the United States of America (USA) and Mexico territories

Year	Management regulation, policy, conservation evaluations	Source
1945	The USA Proclamation of exclusive jurisdiction of territorial sea	1
1966	Mexico - Proclamation of exclusive jurisdiction for fisheries purposes - 12 nautical miles	2
1968–1973	Mexico–United States Fisheries Agreement: Fishery [of GSB] will continue for five years beginning on January 1, 1968, up to a total volume that will not exceed the total catch taken by US vessels in the five years immediately preceding that date. The US fishing vessels will be permitted, during the same term of five years, to continue sport or recreational fishing in Mexican waters.	1, 2
1973	US Federal Endangered Species Act of 1973; GSB not included	1
1981	California State Legislature banned the commercial and recreational fishing of GSB in California waters. A maximum of two incidentally caught GSB per trip in the commercial set gillnet and trammel net fisheries. Any fish so taken shall not be transferred to any other vessel. Vessels fishing in Mexican waters were allowed to land 450 kg of GSB per trip but only 1,360 kg (3,000 lbs) per year.	3
1982	The USA and Mexico proclamation of their Exclusive Economic Zones	4
1984	California Endangered Species Act of 1984; Not included	5
1988	California State Legislature amended GSB moratorium to allow only one incidental fish per vessel, which may be possessed or sold if caught in commercial fishing operations by gill or trammel nets in California.	6
1994	California State Legislature outlawed gill nets and trammel nets within 3 nautical miles of the mainland and 1 nautical mile of the islands)	7
1996	IUCN Red List of Threatened Animals. First evaluation as a critically endangered species.	8
2000	American Fishery Society concept of Distinct Population Segments: Threatened, Vulnerable (US Protection: None; CA: Protected)	9
2013	Mexican recreational fishery regulation NOM–017-PESC–1994 [update]; A maximum of one GSB per fisherman per day. Permits are required when fishing by vessels.	10
2019	CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora: Not included)	11
2020	USMCA - The US, Mexico, and Canada Agreement	12

Notes: 1. The US Proclamation 2668, 10 Fed. Reg. 12304 (1945); 2. DOF 1966 Mexican Government Proclamation; 3. California State Legislature [FGC §8,380, Title 14, CCR, §28.10]; 4. UNCLOS, 1982); 5. California State Legislature; 6. California State Legislature Ch. 308, Sec. 1 [FGC §8380]; 7. California State Legislature Proposition 132; 8. Cornish (2004); 9. Musick et al., 2000; 10. DOF (2013); 11. CITES, 2019; 12. USMCA (2019).

estimate annual spending per project. Mean annual values of overall research funding in the USA and Mexico were calculated by summing within years and dividing by the total number of years in which research funding was reported.

2.2 | Fishery and management trends

We analysed annual trends in the United States and Mexican commercial and recreational fisheries to explore whether contemporary fishing could pose a threat to the conservation of GSB. Historical landings data for GSB from commercial and recreational fisheries in the USA (1913–1999) were extracted from graphs in CDFW reports (Baldwin & Keiser, 2008; Domeier, 2001) using GraphClick v.3.0.3 (Arizona-Software). Data from the commercial fishery were recorded in metric tonnes, whereas data from the recreational fishery were reported based on the number of landed individuals. Historical landings data from the commercial fishery for GSB in Mexico (1957–1999) were obtained from the Sea Around Us Program (http://www.seaaroundus.org/). These data were estimated using the baseline official landings reported for “meros y garropas” (seabasses and groupers) by CONAPESCA to the Food and Agricultural Organization of the United Nations (FAO). The specific catch of GSB within that larger complex was calculated based on available peer-reviewed literature and independent reports of catch composition and estimates of unreported catch by Mexican fleets (Cisneros-Montemayor et al., 2013). To assess possible causes for observed trends, we compared temporal patterns in landings data to the timing of different management actions (Table 1).

Contemporary landings data for GSB (2000–2016) were obtained from CDFW for the USA and from a combination of state (e.g., SEPESCA) and federal (e.g., CONAPESCA) fisheries agencies for Mexico. All commercial and recreational landings data in the USA were recorded as incidental, as this species cannot be legally targeted, and commercial fishers can incidentally land no more than one GSB per trip. The CDFW database included catch location as 10 × 10 min blocks, date, total catch and ex-vessel price, which is the value of fish (dollars/pound, converted to dollars/kg) when offloaded from a vessel. Commercial fishery landings in Mexico were obtained from mandatory (but often uncertain, as discussed below) landings reports, which included the name of the fishing co-operative (or permit holder), catch site, date, total catch and ex-vessel price (pesos/kg, converted to dollars/kg).

TABLE 2 Scientific knowledge on giant sea bass (GSB) in peer-reviewed papers

Keywords	Search Engine	Hits	GSB-listed
"*Stereolepis gigas*"	WS	17	17
	GS	479	54
giant sea bass	WS	17	17
	GS	456	24
"black sea bass" + *Stereolepis*	WS	1	1
	GS	69	12
"mero gigante"	WS	0	0
	GS	44	0
Pescara	WS	310	0
	GS	58,500*	1
Total unique peer-reviewed papers		56	
Peer-reviewed papers - Information exclusively from the USA		39	
Peer-reviewed papers - Information exclusively from Mexico		13	
Peer-reviewed papers - Information from both the USA and Mexico		4	
Total unique GSB-centric papers		21	
GSB-centric papers - Data exclusively from the USA		21	
GSB-centric papers - Data exclusively from Mexico		0	
GSB-centric papers - Data from both the USA and Mexico		3	

Notes: WS, ISI Web of Science; GS, Google Scholar; GSB-listed, Papers that mention GSB; GSB-centric Paper, Papers that are focussed on GSB. Giant sea bass and black sea bass are common names in English used in the literature. Mero gigante and pescara are common names in Spanish (sensu Page et al., 2013).

[a]Pescara is also a noun in Italian.

We used per-trip records submitted to the United States or Mexican governments by fishers (hereafter called "fishing tickets": Miller et al., 2014) and the average yearly landings in the USA and Mexico to test if catch volume correlated with the number of fishing events and identify changes in catch per unit of effort (CPUE). We examined seasonal patterns of contemporary fishery landings (2000–2016) to determine if landings were elevated during certain months, such as those when GSB form spawning aggregations (Erisman et al., 2010). Assuming a relatively steady fishing effort, we would expect landings volumes and locations to increase in response to population recovery and a subsequent range expansion. To examine this, we used data from the US commercial (CDFW) and recreational (CRFS, RecFIN) fisheries to analyse the number of fishing tickets by year and location to test for possible evidence of population recovery.

Mexican official landings have previously been used successfully to assess the status of fish populations (e.g., Goliath grouper (*Epinephelus itajara*, Serranidae), Pacific sardine (*Sardinops sagax*, Clupeidae), barred sand bass (*Paralabrax nebulifer*, Serranidae), red snapper (*Lutjanus campechanus*, Lutjanidae)) (Bravo-Calderon et al., 2021; Cisneros-Montemayor et al., 2020; Erisman et al., 2010; Giron-Nava et al., 2019; Sala et al., 2004). However, as GSB was previously managed within a multi-species complex and mandatory reports have some uncertainty, we compared landings data obtained directly from the logbooks of four fishing co-operatives (SCCP Ensenada, Buzos y Pescadores de Natividad, Punta Abreojos, and Puerto Chale) to official landings data to identify differences in data sources and provide certainty to our analysis. We first tested for autocorrelation between years by running a linear regression between fishery landings and year. We then tested for a 1-year lag by regressing the resulting residual values against the residual value of the prior year. After determining that there was no or minimal autocorrelation, we ran a paired two-tailed t test between co-operative and CONAPESCA data.

We established a biological monitoring programme of the commercial fishery in Mexico to obtain biological data and samples, describe the catch composition of the GSB fishery, and estimate the percentage of the total catch composed of juvenile individuals. We assumed that GSB reaches sexual maturity at 11–13 years and ~800 mm TL based on previous work and our own data (Hawk & Allen, 2014; Ramírez-Valdez, unpublished data). To accomplish this goal, we conducted surveys and sample collections on a monthly basis from March through December 2017 at fish markets, fishing co-operatives and recreational fishery tournaments. Additional data and samples were collected opportunistically from records shared over social media and through fishery-independent surveys (Figure S1). For each fish surveyed or collected, we measured the total length (TL) (to the nearest 0.1 cm), weight (to the nearest 0.1 kg) (Ramírez-Valdez et al., 2018), as well as catch site, date, type of record (e.g., fish market, recreational fishery, fishing co-operatives, etc.) and fishing gear. To test for normality in length data, we used a Shapiro-Wilk test. We used the average tonnage of Mexican landings of GSB from 2000 to 2016 and the average weight of the individuals sampled from the biological monitoring programme to estimate the number of individuals harvested annually in the Mexican fishery. We used the median weight (1965–2006) of the US fishery to estimate the number of individuals removed annually (Bellquist & Semmens, 2016).

2.3 | Spatial patterns of the contemporary fishery

We used the average annual landings over the available data period (2000–2016) to identify the main fishing grounds for GSB. Landings data were associated with spatial data to the finest scale possible. In the USA, we used a 10 × 10-min grid of fishing blocks constructed by the CDFW, whereas for Mexico we used the coastal fishing concession area polygons of the fishing co-operatives as available from official data or provided by CONAPESCA. We assumed each record in the database represented a separate "fishing ticket," which we then used to identify areas of higher effort and annual landings. We tested our assumption by evaluating the catch distribution recorded in the fishing tickets by polygon to see whether the catches represented a likely similar trip length, as indicated by similar weights landed, or more likely include catches from several trips. We divided the species range into biogeographic regions to identify the main grounds of the fishery, as biogeographic regions represent temperature and habitat differences that may influence GSB biology.

2.4 | Asymmetry in economic value

We estimated the consumptive and non-consumptive ex-vessel value of GSB in the USA and Mexico to provide useful information to resources management by showing the economy associated with the different uses of GSB. The consumptive value was obtained using the commercial fishery landings and ex-vessel price data obtained from government agencies CDFW (USA) and CONAPESCA (Mexico) from 2000 to 2016, converted to USD and adjusted for inflation. The non-consumptive value for the USA was obtained from Guerra et al., (2017), who used a contingent valuation method to estimate the amount of money that SCUBA divers in southern California were willing to pay to encounter a GSB based on interviews of 265 scuba divers and the actual mean trip price currently paid by divers. To determine the mean trip price per diver in Mexico, we interviewed the only three diving operations in Mexico that specifically offer dive encounters with GSB.

3 | RESULTS

3.1 | Asymmetry in scientific research

The literature review identified 56 unique peer-reviewed articles mentioning GSB. Only four mentioned GSB in the context of both countries, while 43 articles mentioned GSB in California's waters, and 17 did so for Mexican waters (Table 2; Figures 1, 2). The number of published articles on GSB showed an upward trend after 2007, and 65% of the articles were published within the past 10 years (Figure 2a). Among the 56 articles, only 21 focussed on GSB beyond a simple mentioning. All of these 21 articles contained data and information from the USA, but only three contained data or information from Mexico (Table 2).

We identified nine major topics associated with articles on GSB (Figure 2b): behaviour, conservation, distribution, ecology, fishery, life history, morphology, population and population genetics. Research on GSB in the USA covered most topics fairly evenly but had a slight preference towards ecological aspects, whereas research in Mexico tended to be distribution- and fisheries-related. Overall, most articles referred to adult GSB or were non-specific with respect to life stage (Figure 2c). A summary of all the information compiled through the literature review is presented in Table S1.

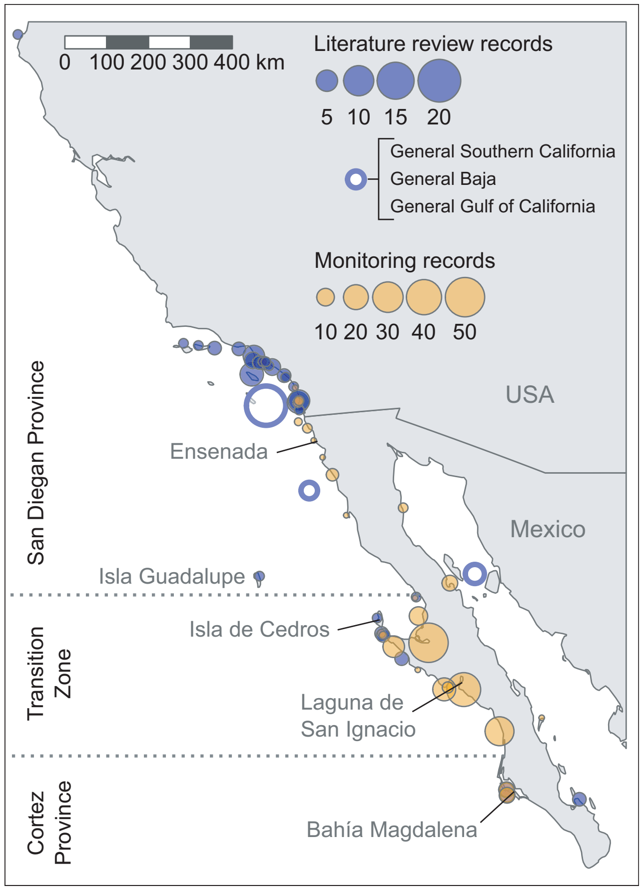

FIGURE 1 Study area and the spatial representation of the literature review (blue) and the biological monitoring programme (orange). Data from peer-reviewed papers not associated with a specific study site are included as General Southern California, General Baja or General Gulf of California. The literature review showed more sites included in more peer-reviewed papers (counts) north of the US–Mexico border. Sites in Mexican waters mentioned giant sea bass in species lists. Biological monitoring includes mostly data from the Mexican fishery

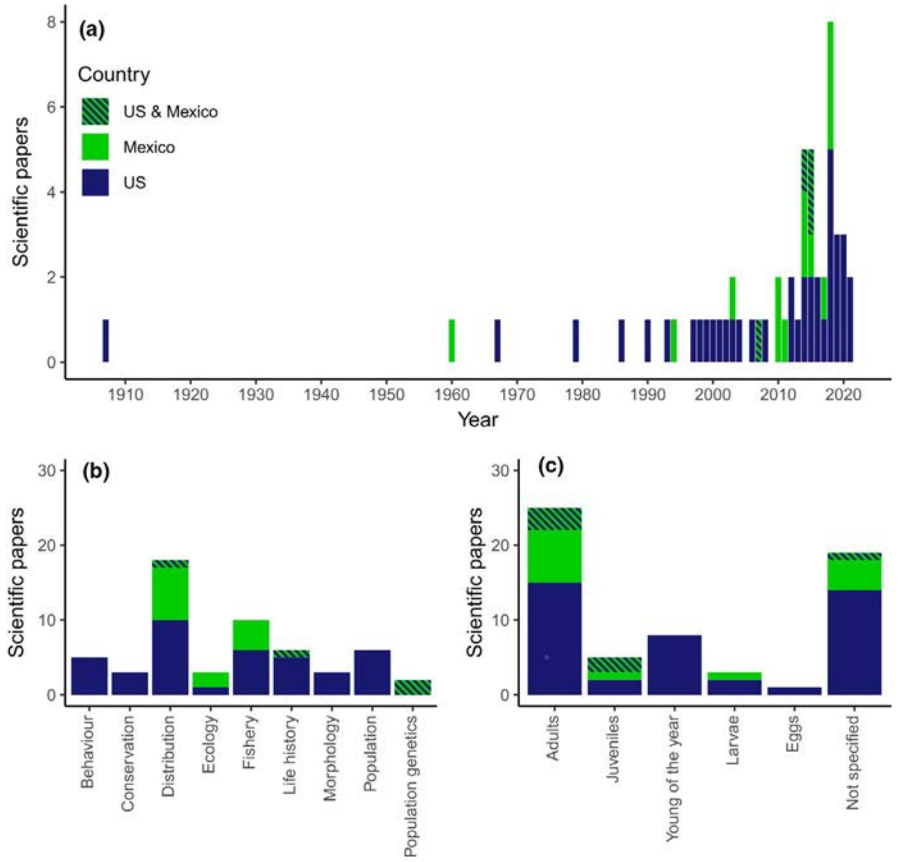

FIGURE 2 Synthesis of the literature review of the knowledge of the giant sea bass (GSB) across its entire distribution. (a) GSB research has recently increased, especially in Mexico. (b) Most papers on GSB are focussed on its distribution and fishery aspects, with less emphasis on life history. (c) The majority of papers focus on adult GSB and many do not mention specific life history stages

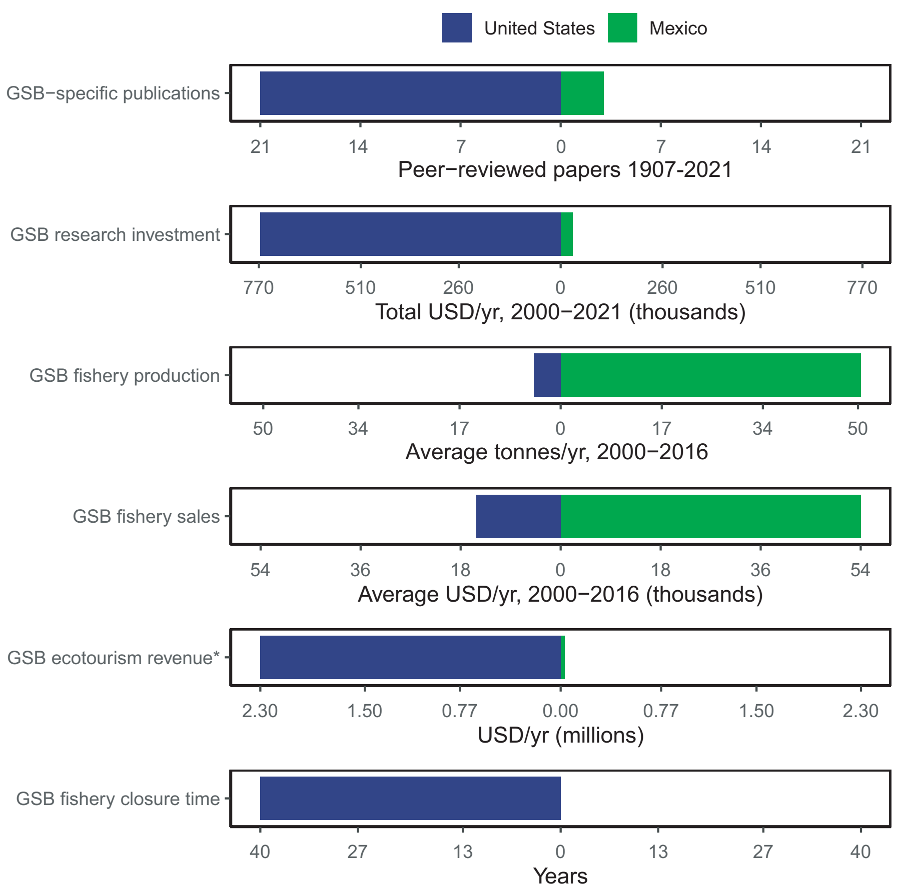

FIGURE 3 Management of the giant sea bass (GSB) across the US-Mexico border is highly asymmetric. Despite little economic or scientific input, Mexican fishery catches, and revenues are high, while the opposite trend occurs in the US GSB ecotourism revenues were obtained from Guerra et al. (2017)

A total of 11,251 records of juveniles, adults and larvae coming from different sources yielded an updated GSB distribution map, ranging from Humboldt Bay (USA) to the southern tip of the Baja California Peninsula and the interior of the Gulf of California in Guaymas (Mexico). We found no records of juvenile or adult GSB south of the Gulf of California or within the Mexican biogeographic province; however, one larval record was noted off the coast of Oaxaca, Mexico. Since 2000, 50% of the records were concentrated in the biogeographic transition zone between Punta Eugenia and Magdalena Bay (Mexico), and 73% of the latitudinal distribution of GSB was in Mexican waters (Figure S1).

Research and conservation groups in the USA and Mexico reported total spending of US $796,697 in GSB research over the past 20 years (Figure 3). Approximately 96% (US $164,030 per year since 2000) of the funding was invested by groups from the USA and involved research in California. A total of US $30,500 (US $13,833 per year since 2000) has been invested in the GSB in Mexico, and research efforts began in 2017. Nine academic institutions and organizations have conducted research on GSB in California, while only one Mexican university and one non-governmental organizations have participated in research on GSB (Table S2).

3.2 | Fishery and management trends

Annual fishery landings of GSB in the USA and Mexico have been highly variable from the late 19th century to the present (Figure 4). The history of the GSB fishery can be divided into five distinct periods: (i) the development of the GSB fishery in the USA; (ii) the collapse of the fishery in US waters; (iii) the development of the GSB fishery in Mexican waters; (iv) the decline of US landings from fish caught in Mexican waters and the rise of Mexican landings; and (v) the contemporary fishery (2000–2016) in the USA and Mexico.

The first period (before 1923) represented the development of the commercial and recreational fisheries for GSB in California, where the US fleet fished mostly in local waters but were supplemented by a small portion of landings coming from Mexican waters. Commercial fishing of GSB in the USA began in the 1870s, while recreational fishing began in the mid-1890s. During this period, fish were targeted with set lines and hand lines. In the second period (from 1923 to 1931), the US fleet increased landings from central and southern California waters until a maximum of 111 tonnes of GSB were landed in 1929. During this time, the US commercial landings from fish captured in Mexican waters also increased rapidly until catches from Mexican waters eventually exceeded catches from within US waters.

During the third period (from 1932 to 1945), the US fishery shifted its fishing efforts to become mostly based on catches in Mexican waters due to a marked decrease in landings. US landings in local waters collapsed and remained below 10 tonnes/year for more than 20 years, while fleet landings in Mexican waters increased to 386 tonnes/year and averaged 220 tonnes/year during the third period. At the end of this period, a sharp decline in the US fleet landings coming from Mexico was observed, apparently due to the USA entering World War II, an effect observed in most fisheries in California (Leet et al., 2001). The absence of historical fishing statistics for that period of the Mexican fleet did not allow us to calculate the exact volume of catches, but the GSB fishery in Mexico was present to some degree such that in 1933 the California Fisheries Yearbook mentioned "a considerable part of the [GSB] catch consists of fish caught in Mexican waters…most…is taken by California fishers off the west coast of Lower California, but a few pounds are caught by Mexicans in the Gulf of California and shipped to Los Angeles by refrigerated trucks as a side issue to the totoaba fishery." (Staff of the Bureau of Commercial Fisheries, 1935).

The fourth period (1946–1999) began with the development of the Mexican fishery along the Baja California peninsula and the establishment of the first fishing co-operatives in the 1950s. Before the 1980s, commercial landings by the Mexican fleet averaged 55 tonnes/year and reached a maximum of 330 tonnes in 1983. These trends coincided with fishery landings for the Baja California Peninsula of the species clustered as "groupers and seabasses" in the 1980s, which included GSB and averaged 400 tonnes/year (DOF, 2006). This period was also marked by the decline of the US commercial fishery in Mexican waters when catches fell from 152 tonnes in 1964 to 14 tonnes in 1972, which was concurrent with a binational agreement that restricted US fleet operations in Mexican waters (Table 1; Figure 4a). The commercial fishery for GSB in the US waters closed in 1981, which by then was landing <2 tonnes/year. In 1994, a ban on the use of gillnets was declared off the southern California coast (Figure 4a). Thereafter, GSB landings in US waters were a result of legal, incidental catch.

The fifth period (2000–2016) was characterized by the stability of incidental landings of GSB by the US fleet that averaged 2.6 tonnes/year and landings from the Mexican fleet that averaged 50.9 tonnes/year. Landings by the Mexican commercial fleet showed two peaks during this period, the first in 2010 at 78.8 tonnes, and the second in 2015 at 102 tonnes. However, commercial GSB catches in Mexico have never dropped below 33 tonnes/year since 2000.

The development of the recreational fishery by the US fleet began around the same time the US commercial fishery collapsed in California (Figure 4b), peaked in 1963 (500 individuals per year), and then markedly declined less than a decade later (<50 individuals per year). The US recreational fleet increased their fishing effort in Mexican waters during this same period, from 100 individuals per year in 1963 to 800 individuals per year in 1971, before declining in 1980.

We found a slight increase in the fishery landings trend of the Mexican commercial fishery during 2000–2016 [R^2 (17,16) = 0.131, p =.152] and a positive correlation between landings and number of fishing tickets [r (n = 1,312) = 0.775, p = <.005], suggesting that the trend in catches is mainly the result of an increase in fishing tickets, which could be due to an increase in effort or catch reporting. The US incidental catches showed a non-significant negative trend, which suggests that landings in the last 16 years have remained stable [R^2 (17,16) = 0.119, p = .174]. Stable US landings and the number

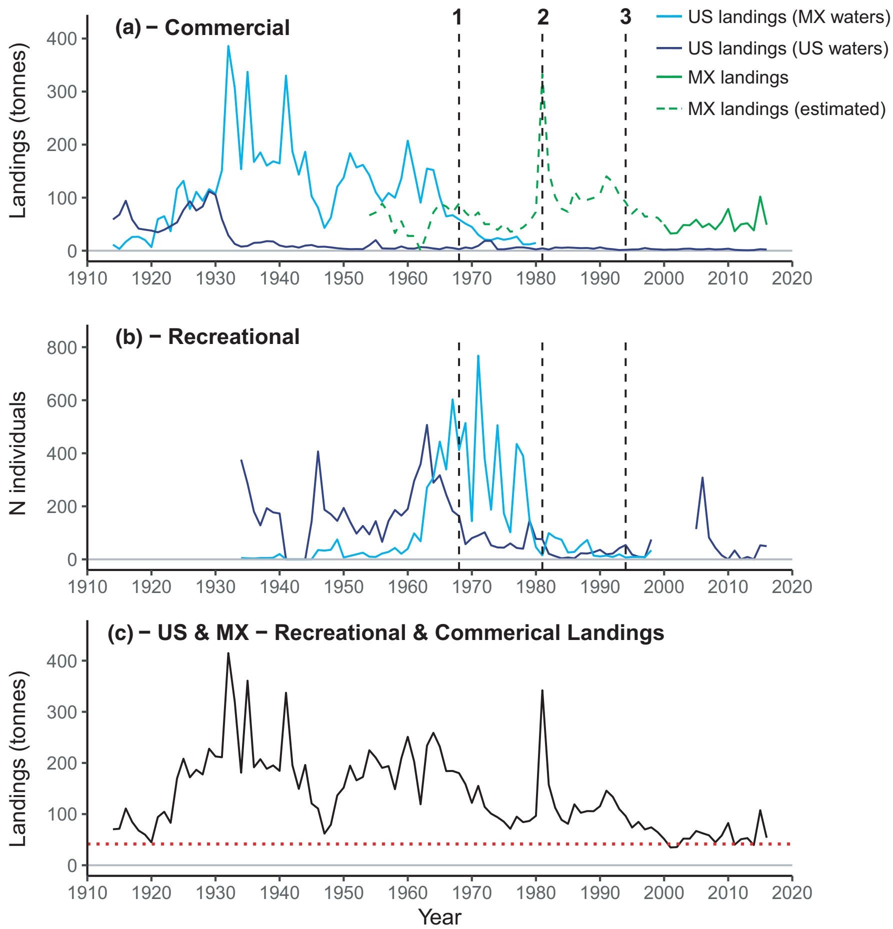

FIGURE 4 Historic and contemporary fishery landings of giant sea bass (GSB) in the USA and Mexico. (a) Commercial fishery by the United States and Mexico fleet, (b) Recreational fishery by the US fleet in United States and Mexico waters, (c) Commercial and recreational fishery landings of GSB from the USA and Mexico merged. Red dotted line indicates 10% of the maximum catch, the criteria used to define a collapsed fish stock (see Pauly et al., 2013). Important historical milestones are indicated by dashed red lines. Events that impacted GSB fishery management: 1—Mexico–US fisheries agreement; 2—US ban on commercial GSB harvesting; 3—US ban on gill nets and trammel nets within certain distances of the coastline, for more information on these events see Table 1. Historical data on commercial catches shows that population collapse in the US waters occurred in the 1930s, much earlier than previously thought. Despite the perceived collapse of Mexican GSB populations in 1972 by the US fleet landings, Mexican fleet landings indicate that political legislation (rather than population collapse) was truly limiting catches in the 1970s. Data source: USA: CDFW; Mexico: CONAPESCA (2000–2017), Sea Around Us (1955–1999)

of fishing tickets were correlated [r (n = 846) = 0.748, p = <.005], suggesting that fishing records have not increased and that fishing tickets can provide a reliable estimate of the fishing effort. Additionally, we found an increase in the number of GSB records (individuals retained or released alive) in Northern California [R^2 (14,13) = 0.450, p = .008], reaching as far north as San Francisco Bay (USA) in many cases.

We found a statistically significant difference of the seasonal catches for the Mexican commercial fishery [one-way ANOVA, F (3,64) = 16.38, p <.050, n = 17], with summer months recording the highest landings (Figure 5). The US incidental catches were also significantly different with higher landings in summer [one-way ANOVA, F (3,64) = 13.27, p <.050]. We found no significant difference (Two-sided paired t-test, t (34,33) = 2.69, p = .135] between the landings obtained from CONAPESCA and the landings coming from the fishing co-operatives, confirming the reliability of the official landings for this analysis (Figure S2). Fishery landings data from the four fishing co-operatives followed the same trend as official landings data.

Over 36 months (2017–2020) of monitoring, we sampled 209 GSB individuals from 28 locations across the Baja California Peninsula, the Gulf of California, and California: 112 from fish market surveys, 53 from fishing co-operatives, 9 from fishing tournaments and 35 from other sources (e.g., social media records, fish collections, fishery-independent surveys). Sampling records covered the geographic distribution range of GSB in Mexican waters with the highest number of samples obtained from regions with the highest commercial landings (Figure 1). Approximately 74% of the records came from surveys in fish markets from Ensenada and Tijuana, the main commercial centres for all fisheries along the Baja California Peninsula. GSB sold in these markets were brought from numerous fishing grounds in the Baja California peninsula. The records from

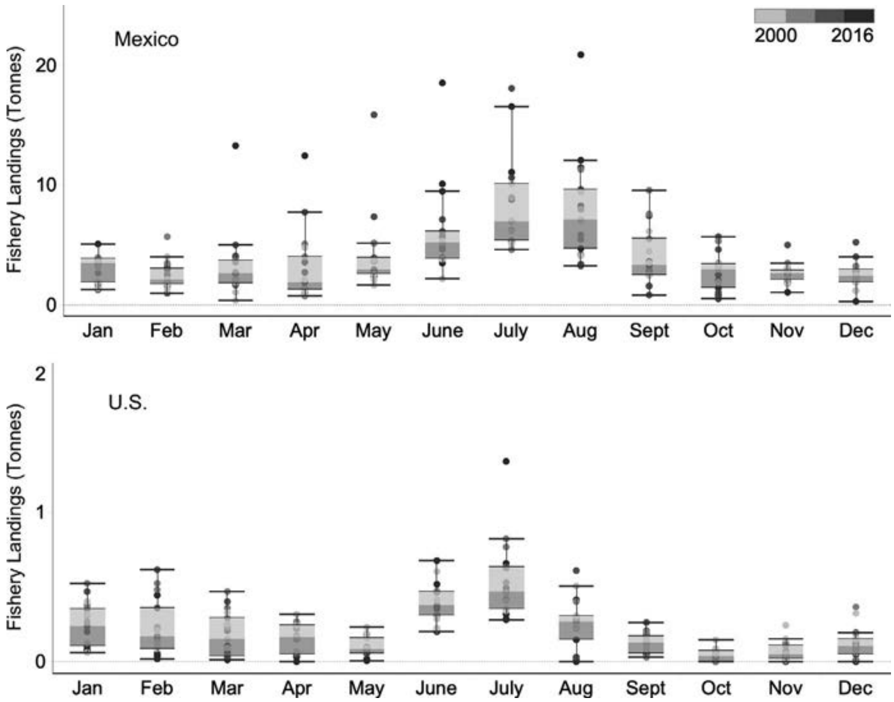

FIGURE 5 Giant sea bass contemporary catches (2000–2016) are highest in the summer in both the USA and Mexico. In Mexico, this corresponds in part to the closure of the lobster fishery from March to September. Data source: Mexico = CONAPESCA; USA = CDFW

fishing co-operatives and fishing tournaments represented a lower percentage (36%). However, these provided valuable information on larger individuals and typically had more precise geographic information on the site of capture. Our samples showed a normal distribution for total length and log-transformed body weight (Shapiro-Wilk test, W > 0.8; $p > .050$). The body length of fish sampled ranged from 300 to 2,300 mm TL (Figure 6a). Approximately 48% of the records were <800 mm TL, indicating that the fishery is targeting a large number of presumed juveniles. The median weight of GSB individuals was 12.0 ± 3.2 kg Mdn ± SE (Figure 6b).

By using the median weight (51 kg, n = 231) of the recreational fishery records from the US fleet (1966–2008) reported by Bellquist and Semmens (2016), we estimated that the US landings of 2.6 ± 0.2 (M ± SE) tonnes/year represented an annual harvest of 50 ± 2.61 individuals. Using the average Mexican landings (50.9 ± 4.1 M ± SE tonnes/year) and the median weight of individuals from our biological monitoring in Mexico (12 kg, n = 182), we estimated that the number of individuals removed annually by the Mexican commercial fishery was approximately 4,244.9 ± 345.07 M ± SE individuals per year. The median better described our weight data central location, which were skewed to the left; however, if we used the mean (32.1 kg), our estimate was 1,721 individuals. Combined, the total catch of GSB from the USA and Mexico represent up to 4,295.9 ± 346.6 M ± SE individuals per year.

3.3 | Spatial patterns of the contemporary fishery

Spatial patterns in fisheries landings matched the geographic distribution of GSB and were distributed from Monterey Bay, California, to the tip of the Baja California Peninsula and inside the Gulf of California (Figure 7). The highest landings were reported in Mexico in the region south of Sebastian Vizcaino (28.5°N) and north of Bahía Magdalena (24.3°N), a transition zone of the temperate and subtropical systems (Figure 7a,c). Isla de Cedros, Laguna de San Ignacio, San Juanico and Bahía Magdalena were especially productive fishing grounds that collectively averaged more than four tonnes/year. The highest annual average landings in the Gulf of California (Cortez province) occurred in the northern region, although Santa Rosalia, in the central region, has reported more total GSB catches ("fishing tickets") over time. In the USA, landings were concentrated in the coastal waters off southern to central California (i.e., San Diego, Dana Point, San Pedro-Los Angeles, and Ventura-Santa Barbara), but the Channel Islands and the US-Mexico border also showed a high number of landings (Figure 7b).

3.4 | Asymmetry in the economic value

The ex-vessel revenue of the GSB incidental catches by the US fleet averaged US $15,133.9 ± 1,211.5 M ± SE per year (Figure 3). The average (2000–2016) official ex-vessel value after inflation was US $6.4 ± 0.2 M ± SE per kg and has increased 40% since 2000. Ex-vessel revenues from the commercial fishing fleet in Mexico averaged US $54,051.8 ± 4,533.4 M ± SE (Figure 3). The average ex-vessel price was US $1.1 ± 0.08 M ± SE per kg in Mexico and has decreased by 32% since 2000. Retail prices in Mexican fish markets were 559% higher (US $6.5 per kg), indicating that most of the revenue made from catches goes to fish markets rather than fishers.

Guerra et al. (2017) reported the non-consumptive value of the GSB in California, considering divers' willingness-to-pay for a GSB sighting, was US $2.3 million per year (Figure 3), and the mean

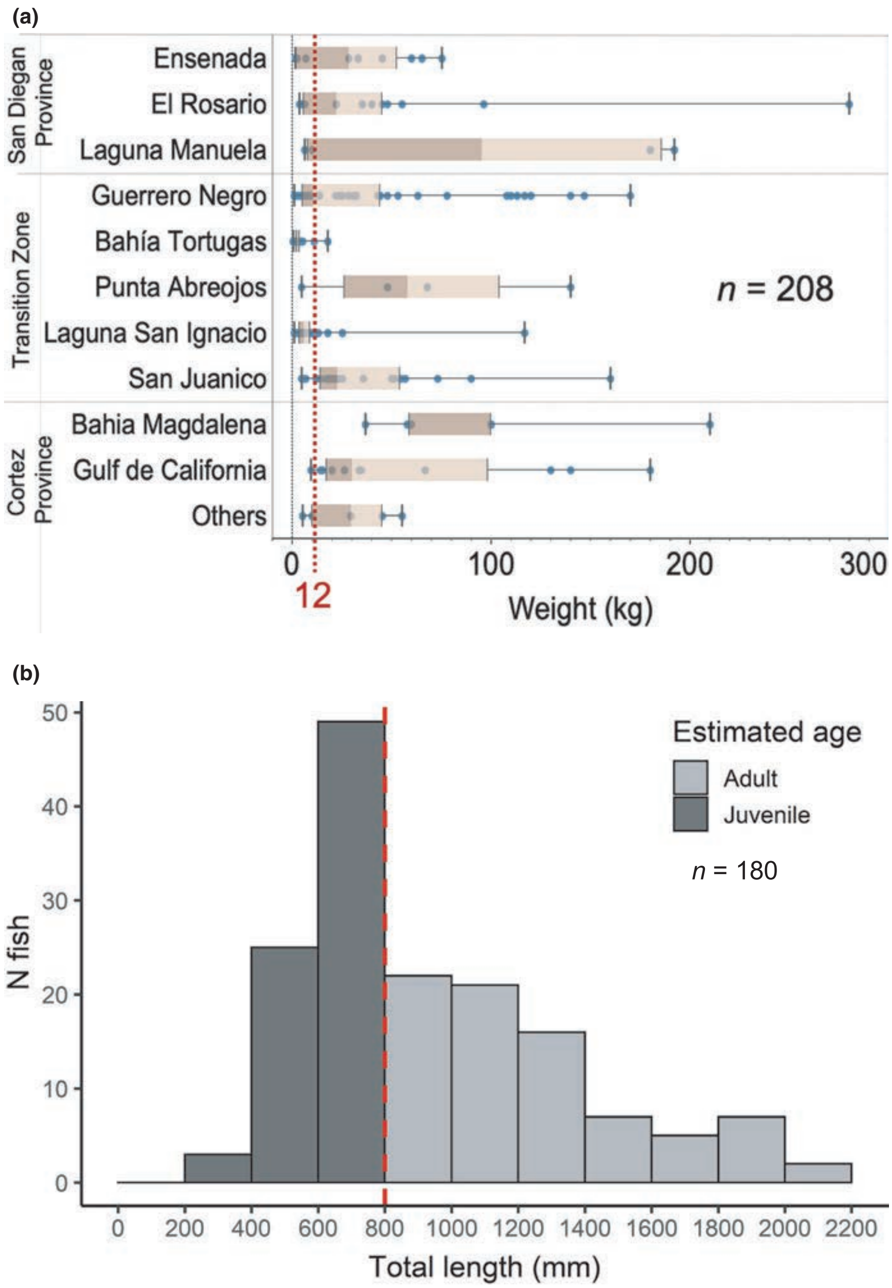

FIGURE 6 (a) Box plot indicating the giant sea bass body weight (kg) sampled through the Mexican fishery monitoring programme. Median weight of 208 samples (12 kg) in red dotted line. Locations are divided into one of three biogeographic regions: San Diegan province, Cortez province and a transitional zone. All regions show a wide range of total weight. (b) Total lengths of 180 samples of giant sea bass sampled by the fishery monitoring programme. Approximately 48% of samples were shorter than 800 mm TL, indicating that many individuals may be juveniles (after Hawk & Allen, 2014)

trip cost that SCUBA divers paid was US $90.7 (Mdn = US $115). Through our interviews with dive expedition companies in Mexico, we estimated that the mean trip price that divers paid was US $216.6 (Mdn = US $250) and the total economy associated with diving with GSB during the 2018–2019 period was US $30,000.

4 | DISCUSSION

The results of this study revealed marked asymmetry in the scientific research, fishery and management trends, spatial distribution of fishing and economic value of GSB across the US-Mexico border. Until recently, the GSB was rarely the focus of research, and the vast majority of scientific studies and monetary investment took place within US waters despite three quarters of the species distribution and likely higher abundances are in Mexican waters. Historical patterns of fishery landings were described by five distinct periods of exploitation by the US and Mexican fleets. After the apparent demise of the GSB fishery in California waters by the 1930s, the USA primarily fished in Mexican waters, leading to GSB landings that dwarfed even the highest captures in California. By the 1980s, US landings from Mexico ceased, concurrent with (and possibly a reflection of) a combination of a fishing ban on GSB in California, new binational treaties, and a proclamation of Exclusive Economic Zones (EEZ) between the USA and Mexico. The Mexican fishery landings have been relatively stable since the 1950s, but contemporary results indicate that a large proportion (48%) of the landings are juveniles. Although the GSB is not a primary target

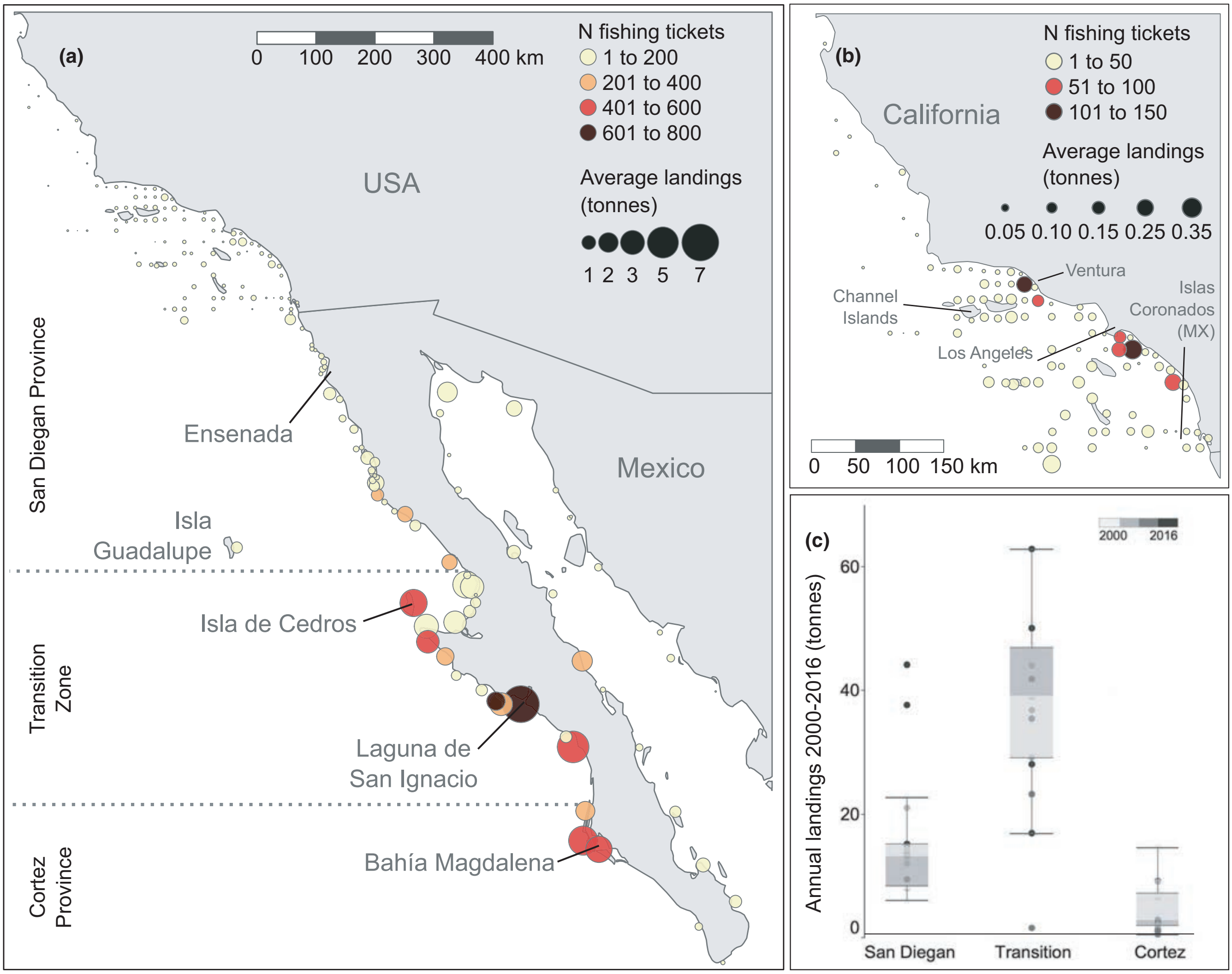

FIGURE 7 Spatial representation of annual average fishery landings of giant sea bass (GSB) from the United States and Mexico commercial fleets (2000–2016) shows much higher landings in Mexico. When divided into biogeographic regions, the transitional zone between the San Diegan and Cortez provinces has the highest proportion of total landings. The number of fishing tickets corresponds to the number of GSB caught. (a) Entire GSB range; (b) California subset; (c) average annual landings from 2000–2016. Data source: Mexico = CONAPESCA; USA = CDFW

species for fisheries in either country, the largest proportion of reported landings occur in summer, which coincides with the spawning season. The spatial distribution of contemporary fishing ranges from sparse landings and effort from southern California in the form of incidental catch to high landings and possibly increasing effort concentrated off the southwestern half of Baja California, where some locations harvest more GSB than the total amount landed annually as incidental catch in US waters (Figure 7). Currently, the annual consumptive value of GSB is only 3.5 times higher in Mexico than in the USA despite 19 times more annual landings in Mexico. Individual fishers in Mexico receive a price 13 times lower than the retail price in Mexican markets, which may contribute to increased overall fishing effort to sustain household incomes. The non-consumptive value in the USA is 76 times higher than in Mexico and still 33 times higher than the ex-vessel revenues of the two countries combined. While GSB is considered a shared binational resource, the disparities in scientific research, fishery management and economics of the species are striking, warranting future collaboration by researchers, fishers, and managers of both nations to understand the status of the population and develop joint management strategies to ensure that efforts for recovery and sustainable fishing are successful.

4.1 | Asymmetry in scientific research

In this study, we found that strong asymmetry exists in scientific research and funding across the US–Mexico border. Seven times more scientific articles have been published on the US population than the Mexican population, despite the fact that the Baja Peninsula is a hotspot for marine research activity in Mexico (Palacios-Abrantes et al., 2019). Among the three articles that contained data on Mexican GSB populations, none addressed the past or ongoing fishery, a trend seen for many other coastal fisheries in the California Current region (Erisman et al., 2010; Johnson et al., 2017; Sáenz-Arroyo et al., 2005). Moreover, only 21 studies that focus exclusively on GSB exist in the literature, indicating that our understanding of the species life history, trophic ecology, physiology, population status and fisheries is limited in both countries. As most of the knowledge about the species has been generated in the last decade, a continuation and expansion of these efforts may be forthcoming and include insights on the potential vulnerability of GSB to climate change. Of all the financial investment in research directed at this species, less than 4% has been directed to populations in Mexico and very little prior to 2017. Given the productive fishery in Mexico and strong conservation efforts in the USA, greater investment into research in both Mexico and the USA is needed to better understand population connectivity and the effects of conservation and active fisheries on stock structure and abundance throughout the species distribution, which will assist in developing transboundary science-based management (Chabot et al., 2015; Gaffney et al., 2007).

Incomplete and asymmetric scientific research may be impacting perceptions on the status of GSB populations for fishers and fishery managers and hinder their willingness to co-operate in shared resource management (Miller & Munro, 2002; Munro, 2018; Vosooghi, 2019). Although this asymmetry in scientific knowledge may not be exclusive to the GSB fishery, it likely has affected fishery management on one side of the border and conservation efforts on the other side. Despite the fact that three quarters of the species distribution is south of the US–Mexico border, the Mexican government fisheries agencies and academic institutions have overlooked generating scientific knowledge of GSB for the past 80 years since fishing co-operatives in the region were founded. The scientific community has highlighted the need for a transboundary perspective when developing research and management of natural resources (Aburto-Oropeza et al., 2018; Ramírez-Valdez et al., 2017), yet many political and administrative barriers to achieving this goal persist (e.g., cross-border permits, research funding opportunities, data standardization, data-sharing). Collaborative research programmes between academic institutions, binational research grants, and co-operation between state and federal governments could be the most achievable strategy to resolve some of the differences in scientific research that are impeding future management.

4.2 | Fishery and management trends

Our analysis of GSB landings consisted of a holistic examination of varying trends over the last century in the USA and Mexico and revealed that the collapse of the GSB fishery and population in US waters occurred as early as 1932. While it is difficult to assess changes in stock sizes exclusively from landings data (but see Pauly et al., 2013), it is likely that the US stock collapsed ~50 years before the implementation of the GSB fishery moratorium in 1981, much earlier than previously thought. Moreover, decreases in US landings in Mexico into the 1970s and 1980s were seemingly a consequence of the binational treaty on fisheries management signed in 1968 and a proclamation of EEZs in 1982, respectively, (Table 1) and not due to decreases in resource availability (Mexico and United States: Fisheries Agreement, 1968). Historical fishing trends also show that as recently as 1970, the US fleet was the main driver of GSB fishing effort and landings both in United States and Mexican waters before being replaced by the Mexican fleet. We were able to reconstruct estimates of historic Mexican landings of GSB, which showed that periods of high landings by the Mexican fleet were not followed by collapses as had occurred in the USA, with the exception of years following the 1981 peak of 333 tonnes. Fluctuations in landings data from Mexican waters may track previous changes in abundance; however, landings from the Mexican fleet have averaged 50 tonnes per year over the last 60 years, indicating the possibility of a stable stock size assuming static fishing effort. However, studies on other fishes have shown that catch rates can remain nearly constant even as abundance declines (hyperstability: Erisman et al., 2011; Maunder et al., 2006), or fishers could be exploiting new locations for GSB are possibilities that were not assessed from historical data. Historical records of recreational GSB fishing in the USA occurred after the collapse of the commercial fishery, but recreational catches ceased being common by the 1970s. Disparities between commercial and recreational landings in Mexico indicate that the large increase in GSB recreational fishing in the 1960s and 1970s was likely related to tourism or other socioeconomic factors and not necessarily the availability of GSB in fished habitats.

Contemporary landings in the form of incidental catch in the USA and small-scale commercial fisheries in Mexico were variable since 2000 but comparatively stable when compared to the large fluctuations in landings observed during the prior century. We detected a slight decreasing trend in landings in the USA and a slight increasing trend in landings and effort in Mexico, which should continue to be tracked in the future to help facilitate effective management whether it be for recovery or sustainable fishing. We estimated that the USA and Mexico land on average 50 and 4,244 individual GSB per year, respectively. Differences in the contemporary mean weight of GSB fished by the United States (51 kg) and Mexico fleets (12 kg) can be explained in part by the fishing methods used. Most catches from California come from gill and trammel net fishing, while the highest proportion of Mexican commercial fishing is conducted with gillnets targeting white seabass and flatfish. Gear selectivity of gillnets used in Mexico may result in the extraction of higher percentages of juveniles as observed in our biological monitoring programme; however, abundances of juveniles across the US–Mexican border have not been examined. The potential impacts of removing proportionally high levels of juveniles should be considered in future assessments and management decisions. While the US landings remain consistently very low due the moratorium, the variability of annual catches from the Mexican commercial fishery may be due to changes in recruitment, as a response to climatic variability, and/or changes in fishing effort, as has been reported for other long-lived, aggregate spawning fish (Erisman et al., 2010; Roughgarden & Smith, 1996; Sadovy de Mitcheson et al., 2013). The recruitment of this species may increase during strong El Niño events, which has been proposed for California (Schroeder & Love, 2002) and may also be true for Mexico, but there are no studies that examine population or recruitment variability in relation with climatic and environmental conditions (Cavole et al., 2016). GSB are not directly targeted by Mexican fisheries, but changes in the availability and market prices of other fished resources may cause shifts in target species in the future, further warranting increased research to understand the sustainability of current trends and future scenarios of GSB fishing effort in the region.

Our analysis combining fishery statistics and biological monitoring of the Mexican fleet allowed us to conclude that the GSB population size could be larger than previously thought and may not meet current IUCN requirements for being classified as critically endangered throughout its distribution. Chabot et al., (2015) estimated the effective population size (Ne) of the species to be 500 individuals, including samples from California and Mexico, adding that this could be greater than 10% of the census population size (i.e., census population size <5,000). This estimate spread rapidly in the scientific community and the media and contributed to the perception of the fragile status of the GSB population (Fox, 2018; Guerra et al., 2017; Sahagun, 2018; Tallal, 2020; Wisckol, 2018). Based upon our results, this is almost certainly an underestimate of both the effective and census population sizes of GSB. For if this was true, the Mexican fishery would have harvested around 85% of the census population annually since the year 2000, which is a highly unsustainable rate. Therefore, the current population size of GSB remains largely unknown, but at a minimum, our analysis shows that GSB is more abundant than previously thought throughout its distribution.

The largest proportion of landings in the USA and Mexico are reported in summer, which coincides with the GSB spawning season (Clark & Allen, 2018; Domeier, 2001; Ramírez-Valdez, unpublished data). Fishing large volumes of aggregated fish, such as GSB, during reproductive periods can increase population vulnerability if not properly managed (Erisman et al., 2017; Pittman and Heyman, 2020; Sadovy de Mitcheson et al., 2013, 2020). While increases in landings during summer are likely unrelated to fishers targeting GSB, increases in gear from other fisheries interacting with GSB may contribute to the patterns observed. For example, in Southern California, months with the highest GSB incidental catch coincides with an increase in gillnet effort targeting primarily white seabass (*Atractoscion nobilis*, Sciaenidae), California barracuda (*Sphyraena argentea*, Sphyraenidae) and yellowtail (*Seriola lalandi*, Carangidae) from January to July (Lyons et al., 2013). In Mexico, seasonal closures of the profitable California spiny lobster (*Panulirus interruptus*, Palinuridae), abalone (*Haliotis* sp., Haliotidae) and warty sea cucumber (*Apostichopus californicus*, Stichopodidae) fisheries in summer months coincide with a shift in focus to finfish fisheries (i.e., white seabass, yellowtail, flatfish), which likely increases the potential for higher-than-normal incidental catches of GSB (Aalbers et al., 2021; Baja California's Fishery Agency, 2018; Cota-Nieto et al., 2018). Additionally, a higher incidental catch has been documented for other species (e.g., great white shark, *Carcharadon carcharias*, Lamnidae) from February to August due to a greater gillnet effort in the Guerrero Negro-Vizcaino region (Oñate-González et al., 2017).

4.3 | Spatial patterns of the contemporary fishery

Spatial analysis of the GSB fishery (2000–2016) revealed that catches in the US waters were associated with major gillnet fishing effort blocks (soak h/net length fathom) reported for white seabass, California barracuda and yellowtail (Lyons et al., 2013), while in Mexican waters landings were concentrated in traditionally productive fishing grounds across the temperate–tropical transition zone. Some of the most productive fishing grounds (Vizcaíno, Isla Cedros, Punta Abreojos, Bahia Tortugas, Ojo de Liebre) have average GSB catches of up to 5 tonnes/year, and the high productivity of these regions is also observed in other fisheries (e.g., abalone, barred sand bass; lobster, yellowtail) (Micheli et al., 2014; Paterson et al., 2015). In the 1970s, US recreational fishing vessels visiting these same fishing grounds caught on average 70–100 individuals, sometimes up to 255 individuals on a three-day trip (Domeier, 2001). Contemporary catches extend throughout the geographic distribution range reported for the GSB, indicating that parts of the population may not have been extirpated as a result of overfishing. However, recent studies have found that while adult GSB exhibit high levels of residency, they also migrate long distances, which could help maintain GSB abundance in heavily fished areas (Burns et al., 2020; Clevenstine & Lowe, 2021).

Since 2005, the number of commercial fishing permits and the average number of vessels operated per permit have remained steady in the Baja California region (Baja California's Fishery Agency, 2018; DOF, 2006). Our analysis shows that the fluctuation in the landings of the Mexican commercial fleet was highly correlated to the number of fishing tickets in the past 16 years, suggesting possible increases in effort by increasing the number of fishing trips. Although GSB is not traditionally a target fishery in the Baja California Peninsula fishing grounds, fishers with permits to harvest multiple species shift to finfish fishery (GSB among them) when other fisheries decline. The inverse relationship of the catch effort between the finfish fishery and more profitable fisheries (i.e., lobster) has been documented previously for the central region of the Baja California Peninsula (Cota-Nieto et al., 2018). As fishes shift their distributions in response to climate change (Pinsky et al., 2018) increases in the abundance of GSB in California waters may result in increased interactions with fishers. Impacts of this potential increase on GSB are unclear, especially given the lack of information on post-catch-and-release survival for the species.

4.4 | Asymmetry in economic value

The economic value of the GSB differs greatly across the US–Mexico border and is largely a result of different consumptive and non-consumptive values of GSB. The consumptive value in Mexico is 3.5 times higher than in the USA, while the non-consumptive value in the USA is 76 times higher. The US official ex-vessel price is 6 times the Mexican official price that is paid to fishers, although the non-official price observed in Mexican fish markets is comparable with the US ex-vessel price. The discrepancy between dockside and retail prices may contribute to increased fishing effort in order to support fisher household incomes. Understanding these dynamics to support more equitable distributions of fishery profits may be an effective strategy to reduce overfishing and encourage more co-operation to achieve sustainable fisheries management in Mexico.

One avenue of non-consumptive economic gain is through recreational SCUBA diving (Guerra et al., 2017). Recreational SCUBA diving with GSB is expanding in Mexico, specifically in central Baja California where GSB sightings are concentrated. However, this region has scarce tourist infrastructure as they are small fishing communities, and a GSB dive tourism industry has only begun to take shape in the last five years. Understanding the economic balances between management, resource value from fishers to market, and alternative sources of income, such as through tourism, should be considered as necessary steps to ensure the sustainability of the current fishery and conservation of GSB for other economic benefits.

5 | CONCLUSIONS AND FUTURE DIRECTIONS

Examination of asymmetry across international boundaries should not serve to belittle certain nations but rather to highlight differences in activities and knowledge and how transboundary management of shared resources can be made more effective (Shackell et al., 2016). Shared fishery stocks are often more prone to overexploitation compared to solely owned stocks, as they often fall victim to "tragedy of the commons" scenarios between nations (McWhinnie, 2009; Ostrom et al., 1999). Transboundary management has not occurred for GSB nor for most other fishery species between southern California and Baja California, including sharks, white seabass and abalone (Holts et al., 1998; Munguía-Vega et al., 2015; Romo-Curiel et al., 2016), likely due to broad differences in scientific knowledge and perceptions of resource availability and connectivity. In the case of the GSB, which has a continuous distribution along the California's (both USA and Mexico), asymmetries across the US–Mexico border are significant barriers to understanding the past, ensuring future sustainable fishing and facilitating population recovery of what is currently considered by the IUCN as a critically endangered species.

Our assessment of historical and contemporary landings data in the context of local and international policy revealed that changes in regulations have hidden historical population collapse in the USA and created the false narrative that they occurred later than thought. While population levels in US waters likely reached severely depressed levels by the 1930s, US landings from Mexico continued to remain high until binational agreements all but ended the US fishery in Mexico. With this knowledge and the continuation of stable landings from domestic fisheries in Mexico, there is no concrete evidence that the GSB fishery ever collapsed in Mexico nor was the population reduced to levels observed in the USA. While the GSB population in the USA is showing signs of recovery (Pondella & Allen, 2008), the IUCN Red List currently classifies GSB as a critically endangered species due to overfishing and the population being considered "severely fragmented, leading to a continuing decline of mature individuals," but recognizes the lack of information on the Mexican fishery (Cornish, 2004). This assessment, however, was made during a period when interpretation of the IUCN criteria was broader, and the species may not qualify critically endangered if assessed today given the new data, herein, and current standards of review. Our analysis of contemporary landings and spatial data suggest that population size of GSB across its entire distribution is likely larger than previously known, especially in Mexico, yielding previously absent information for when the species conservation status is next assessed.

Prior to effective management and more concrete determinations of species status, we need to continue developing our understanding of species distribution, abundances, population structure and connectivity of GSB in different regions of its range, especially in Mexican waters where no fishery restrictions exist. With such an understanding, future collapses, as those experienced in the USA historically, may be prevented with better management and trade restrictions, yielding benefits to both recovery in the USA and sustainable fisheries in Mexico. A combination of scientific inquiry and community-based involvement will be key in providing new information about GSB. While relatively low in volume, incidental catch from the US fleet could be an excellent source of information. Given the possibility of a future increase in incidental catches as a result of a population rebound, collaborations between US fishers and research institutions could greatly increase available sampling opportunities. In Mexico, the biological monitoring programme that we developed as part of this study included the active participation of fishing co-operatives. As many co-operatives self-manage fisheries through minimum size limits, quotas within fishing polygons, area or depth restrictions and seasonal closures, such programmes should be continued and expanded to recreational landings that may increasingly involve local vessels for hire.

Transboundary fisheries management beyond national jurisdiction areas have been abundantly discussed (Fromentin & Powers, 2005; Munro, 1990; Seto et al., 2021; Willis & Bailey, 2020), and some examples have had reasonable success (Seto et al., 2021). However, the management of most shared fisheries stocks between EEZs have had limited success (Palacios-Abrantes et al., 2020; Spijkers et al., 2018; Russell & VanderZwaag, 2010). For example, the Atlantic mackerel (*Scomber scombrus*, Scombridae) is an important shared stock co-operatively managed through the North-East Atlantic Fisheries Commission (Gullestad et al., 2020; Spijkers & Boonstra, 2017). However, climate-driven migration has progressively expanded the range of this species as far as Iceland and southern Greenland, resulting in the so-called mackerel dispute over the size and relative allocation of the total allowable catch (Spijkers & Boonstra, 2017). The Atlantic mackerel dispute is not due to environmental scarcity or habitat degradation; in fact, the biomass of the mackerel stock has increased in the past years (FAO, 2018). Rather, this is a conflict related to climate change, fish stock redistributions, adaptations in fisheries and social issues (Spijkers et al., 2018). On the other hand, the Peruvian anchovy (*Engraulis ringens*, Engraulidae), which represents almost 10% of worldwide marine fisheries landings and has been described as the largest monospecific fishery (Bakun & Weeks, 2008; FAO, 2018), spans the EEZs of Chile, Ecuador, and Peru, yet the latter is home to the largest proportion of the population (Kroetz et al., 2019; Palacios-Abrantes et al., 2020). Although this fishery has been considered sustainable (Chavez et al., 2008), southern Peru's stock (7%–19% of total Peru's stock) has been the subject of disputes with Chile over seasonal closures or binding catch limits (Schreiber & Halliday, 2013). The United Nations agreed to support Peru and Chile to adopt measures aimed at developing an Ecosystem-Based Management approach in the region, which represents standardized stock assessments through co-ordinated management (UNDP, 2016). However, the biggest challenge has been a deep-rooted border dispute.

The USA and Canada co-operatively manage transboundary stocks in the Pacific and the Atlantic (e.g., Pacific halibut, *Hippoglossus stenolepis*, Pleuronectidae; Atlantic halibut *Hippoglossus hippoglossus*, Pleuronectidae; Atlantic cod, *Gadus morhua*, Gadidae; and stocks of salmon) (Koubrak & VanderZwaag, 2020; Miller et al., 2013; Shackell et al., 2016; Song et al., 2017). For most of these stocks, binational commissions have been created and established adaptive management tools (Koubrak & VanderZwaag, 2020; Song et al., 2017). For example, after decades of disagreements over equitable interceptions balance of Pacific salmon (*Oncorhynchus sp.*, Salmonidae) migrating between EEZ, both countries signed a treaty tailoring harvest efforts to protect the stocks that had become severely depleted (Miller & Munro, 2004). The treaty has served to mediate the imbalances generated by the stocks' conditions and considers implicit side-payment in financing for research and enhancement activities (Miller & Munro, 2004).

The information provided by this study may open the opportunity to discuss binational agreements in the management of this and other marine resources. The current vision in the fisheries management of shared stocks on allowing both parties to make responsible decisions within their EEZ has proven to be insufficient. Here, we have provided new information about GSB in the USA and Mexico and suggested possible solutions to increase knowledge, species conservation and economic opportunities. Transfers of knowledge and collaboration by researchers, managers and fishers are essential for developing shared resource management. The future fruition of conservation efforts coupled with possible shifts in species distributions in the face of climate change may result in a more equal proportion of the GSB population distributed in the USA and Mexico. The case of the GSB, together with the other examples of shared fisheries stocks provided, demonstrate that asymmetry in resource management is ubiquitous. Therefore, while there is no one-size-fits-all approach to address transboundary management, co-operation between nations is crucial to tackle fishery governance in a changing world (Palacios-Abrantes et al., 2020; Pinsky et al., 2018; Sumaila et al., 2020).

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as pre-judicing the impartiality of the research reported.

AUTHOR'S CONTRIBUTION

Authorship was arranged in descending order by level of contribution to different components of the manuscript, except for the last author. A. Ramírez-Valdez conceived and designed the study with important contributions from T.J. Rowell and B.E. Erisman. A. Ramírez-Valdez, T.J. Rowell, J.C. Derbez-Villaseñor, M.T. Craig, L. Allen, J. Torre, A. Hernández-Velasco, A.M. Cisneros-Montemayor and J. Hofmeister contributed with collection and compilation of biological and/or fishery data. A. Ramírez-Valdez and K.E. Dale analysed the data and created the figures and tables. A. Ramírez-Valdez, T.J. Rowell, B.E. Erisman and K.E. Dale led the writing. M.T. Craig, A.M. Cisneros-Montemayor, J.C. Derbez-Villaseñor and J. Torre contributed to editing the manuscript. All authors provided a critical revision of all versions of the manuscript.

DATA AVAILABILITY STATEMENT

In accordance with the "DFG Guidelines on the Handling of Research Data," we will make all data available upon request.

ORCID

Arturo Ramírez-Valdez https://orcid.org/0000-0002-1200-7643
Timothy J. Rowell https://orcid.org/0000-0002-5756-6254
Katherine E. Dale https://orcid.org/0000-0002-8544-1571
Matthew T. Craig https://orcid.org/0000-0002-7327-5449
Larry G. Allen https://orcid.org/0000-0002-9806-4429
Juan Carlos Villaseñor-Derbez https://orcid.org/0000-0003-1245-589X
Andrés M. Cisneros-Montemayor https://orcid.org/0000-0002-4132-5317
Arturo Hernández-Velasco https://orcid.org/0000-0002-5113-3888
Jorge Torre https://orcid.org/0000-0002-4762-8159
Jennifer Hofmeister https://orcid.org/0000-0003-1217-8829
Brad E. Erisman https://orcid.org/0000-0002-9336-7957

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Asymmetry across international borders: research, fishery and management trends and economic value of the giant sea bass (*Stereolepis gigas*)

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SUPPORTING MATERIAL

TABLE S1. Synthesis of scientific knowledge about the giant sea bass resulting from the literature review.

Characteristic	Value	Reference
Taxonomy		
Synonyms	*Stereolepis californicus* Gill 1863; *Megaperca ischinagi* Hilgendorf 1878	Fricke, Eschmeyer, & Van der Laan (2020)
Life history		
Clutch size (eggs)	60 million	Benseman & Allen (2018); Domeier (2001); Shane et al. (1996)
Egg size (mm)	1.6 (1.5-1.6)	Shane et al. (1996)
Larvae	Lecithotrophic	Shane et al. (1996)
PLD (days)	26.8 ± 2.4	Benseman & Allen (2018)
Size at settlement TL (mm)	14.4 ± 3.0	Benseman & Allen (2018)
Age at first breeding (yr)	11-13 (18-24 kg)	Domeier (2001); Fitch & Lavenberg (1971)
Life span - Otolith thin-sections (yr)	76 (2003 mm SL)	Hawk & Allen (2014)
Life span - Radiocarbon (yr)	62 (2200 mm TL)	Allen & Andrews (2012)
Reproductive mode	Oviparous, gonochoric, dioecious (sexual dimorphism*)	Clark & Allen (2018); Domeier (2001); Fitch & Lavenberg (1971)
Reproductive mode	Pelagic spawners	Benseman & Allen (2018); Clark & Allen (2018)
Reproductive season	July-November (September)	Benseman & Allen (2018); Clark & Allen (2018); Clevenstine & Lowe (2021)
Reproductive strategy	Pelagic spawners; aggregations (> active at 1700-2000 hrs)	Clark & Allen (2018); Domeier (2001)
Max. obs. agg. (ind)	20-24 ind in aggregation site	Clark & Allen (2018); Clevenstine & Lowe (2021); House et al. (2016)
Aggregation behavior period	June – October	Clevenstine & Lowe (2021)

Sex ratio	1:1 (inferred)	Domeier (2007); Gaffney et al. (2007)
TL max (mm)	2700 (2500)	Allen (2017); Domeier (2001); IGFA (2021)
SL max (mm)	2003	Hawk & Allen (2014)
Wt mx (kg)	253 (255)	Allen & Andrews (2012); Domeier (2001)
HL max (mm)	57	Allen & Andrews (2012)
YOY TL (mm)	145	Allen & Andrews (2012)
YOY growth rate (mm/day)	1.23	Benseman & Allen (2018)
Weight - Age relationship	$y=0.029x-0.085$; $R^2=0.9013$; $p<0.001$	Hawk & Allen (2014)
Length (SL) - Length (TL) relationship	$a=1450$; $b=-10.87$; $R^2=1.21$	Williams et al. (2013)
Length (SL) - Weight relationship	$a=1.07E-04$; $b=-2.8$; $R^2=0.99$	Williams et al. (2013)
Length (SL) -Age relationship	$K=0.044$; $t_0=-0.345$; $L\infty=2026.2$; $R^2=0.911$; $p<0.001$	Hawk & Allen (2014)
Growth Model - von Bertalanffy	$L\infty$ 2026.2; K 0.044; t_0 -0.345	Hawk & Allen (2014)
YOY Length (TL) - Age relationship	$y=1.23x-18.49$; $R^2=0.908$; $p<0.0001$	Benseman & Allen (2018)
YOY black phase TL (mm)	10 - 21	Benseman & Allen (2018)
YOY brown phase TL (mm)	23 - 33	Benseman & Allen (2018)
YOY orange phase TL (mm)	41 - 185	Benseman & Allen (2018)
Natural mortality rate	6%	Schroeder & Love (2002)
Sound production mechanism	5 putative sonic muscles between each of the first six pleural ribs	Allen et al. (2020)
Ecology		
Northernmost distribution record	Humboldt Bay, California, U.S.	Boydstun (1967)
Southernmost distribution record	Southern tip of Baja California peninsula, and Huatabampo, Sonora, within the Gulf of California, Mexico (Oaxaca, Mexico was previously recognized as the southernmost distribution, but the record come from larvae)	This study. Shane et al. (1996)
Foraging mode	Macro-carnivore	Fitch & Lavenberg (1971); Love et al. (1996)
Trophic level	3.74	Vilalta-Navas et al. (2018)
Prey items	rays, skates, lobster, crabs, flatfish, small sharks, squid, blacksmith, ocean whitefish, red crab, sargo, sheephead, anchovies, mantis shrimp	Domeier (2001); Fitch & Lavenberg (1971); Lover et al. (1996)
Generation time (yr)	7 - 10	Domeier (2001)
Ecol. density YOY	$0.4/100\ m^2 \pm 1$ SD	Benseman & Allen (2018)

Mean biomass density adults (Catalina Island, CA)	40 kg /1,000m^2	House et al. (2016)
Population size	Pre-exploitation biomass SoCal 1,300 tons (1,179 tonnes)	Ragen (1990)
Residency	55 ± 18% SD of their time spend at the tagging site. Residency was not significantly different based on water temperature or lunar phase (498 days long study).	Clevenstine & Lowe (2021)
Long distance movements	It has been reported swimming approximately 90 km in 74 h/ 53 km in 56 hr.	Burns et al. (2020); Clevenstine & Lowe (2021)
Mean daily distance traveled	0.31 – 16.66 km Min - Max	Clevenstine & Lowe (2021)
Mean nightly distance traveled	0.03 – 20.29 km Min - Max	Clevenstine & Lowe (2021)
Habitat affinity	Marine neritic. 5-46 m (18-150 ft)	Domeier (2001); Love et al. (2005)
YOY's habitat	canyons 2-18 m depth; mudflats and coastal lagoons	Benseman & Allen (2018); Couffer et al. (2015); Love (2011)
Juvenile's habitat	soft muddy bottom; flat sandy bottom (12-21 m depth)	Love (2011)
Adults' habitat	edges of nearshore rocky reefs and kelp forest (10-46 m depth); artificial reefs (11-17 m depth)	Burns et al. (2020); Clevestine & Lowe (2021); Love et al. (2005); Miller & Lea (1972)
Symbiosis behavior	Cleaned by four species	Dewet-Oleson & Love (2001)
Resilience	Low; minimum population doubling time > 14 years (t_m=11; t_{max}=75)	Musick et al. (2000)
	Population genetics	
Mean Nucleotid diversity	0.09	Gaffney et al. (2007)
Mean Nucleotid diversity	0.001 ± 0.001	Chabot et al. (2015)
Haplotype diversity	13 (h= 0.88)	Gaffney et al. (2007)
Haplotype diversity	4 (0.162 ± 0.064)	Gaffney et al. (2007)
Effective population size Ne	502.84 x 10-3; Ne Est2 152.8; NeEst^2 95% CI 84–539.2	Chabot et al. (2015)
Avg. observed heterozygosity	0.654-0.706	Chabot et al. (2015)
Observed number of alleles	112 (59-81)	Chabot et al. (2015)
Avg. allelic richness	8.87 (4.54-4.81)	Chabot et al. (2015)
Fst values	df 121; sum of sq 517.492; variance 4.289; 1 % var	Chabot et al. (2015)
Fixation index (FST)	0.01 (p=0.034)	Chabot et al. (2015)
	Fishery	
Commercial catch vs SST correlation	r= -0.338 (p=0.340)	Pondella & Allen (2008)

Commercial catch vs PDO correlation	r= -0.284 (p=0.426)	Pondella & Allen (2008)
Commercial catch vs ENSO correlation	r= -0.166 (p=0.646)	Pondella & Allen (2008)
Median Size Recreational Fishery in the U.S. (1966-2008) (kg)	51	Bellquist & Semmens (2016)
Median Size Commercial and Recreational Fishery in Mexico (2017-2021) (kg)	12	This study
Management / Conservation		
U.S. Management	California State Legislature amended the 1981 moratorium to allow only one incidental fish per vessel to be landed in commercial fishing operations by gill or trammel nets in California	California State Legislature Ch. 308, Sec. 1 [FGC §8380]
Mexico management	A maximum of one GSB per fisherman per day in the recreational fishery. Permits are required when fishing by vessels. No restrictions for commercial fishery.	NOM-017-PESC-1994 (2013)
IUCN Category	Critically Endangered	Cornish (2004)
AFS Category	Threatened	Musick et al. (2000)
CITES	Not included	CITES (2019)

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TABLE S2. Economic investment on giant sea bass research and husbandry.

Country	Reference	GSB Project Topics	Period	Years	Funds allocated (US$)	Funds allocated/Year (US$)
USA	1	GSB Conservation	2016-2019	3	$35,000	$11,667
	2	YOY GSB growth & release	2018-2019	1	$37,000	$37,000
	3	Adult movements patters, Habitat preferences	2016-2021	4	$87,000	$21,750
	4	Age-Growth, Population genetics, Distribution, Courtship behavior, YOY distribution, Sound production	2010-2020	9	$30,500	$3,389
	5	Nursery habitat and Distribution of YOY	2015-2020	4	$27,697	$6,924
	6	Adult movements patters, Habitat preferences, Reproductive biology, Population genetics, Fishery	2000-2009	8	$400,000	$50,000
	7	Adult movements patters, Habitat preferences, Fishery	2002-2006	4	$70,000	$17,500
	8	Adult movements. Trophic ecology. GSB conservation	2012-2021	5	$37,000	$7,400
	9	Population size. Economic Value. Spotting GSB website	2014-2020	5	$42,000	$8,400
USA Total			2000-2021	19	$766,197	$164,030
Mexico	10	Age-Growth, Population size, Aggregation site, Fishery, Population genetics	2017-2021	3	$25,000	$8,333
	11	Population size, Aggregation site, Fishery, Population genetics	2018-2020	1	$5,000	$5,000
	12	Population genetics, Age-Growth	2018-2019	1	$500	$500
Mexico Total			2017-2021	3	$30,500	$13,833
U.S. and Mexico Total					$796,697	

1. Aquarium of the Pacific, 2. Cabrillo Aquarium, 3. CSULB, 4. CSUN, 5. M. Couffer, 6. M. Domeier, 7. Pfleger I.E.S., 8. SIO, 9. UCSB, 10. SIO-Proyecto Mero Gigante, 11. Comunidad y Biodiversidad, A.C. (COBI), 12. Proyecto Mero Gigante-UABC.

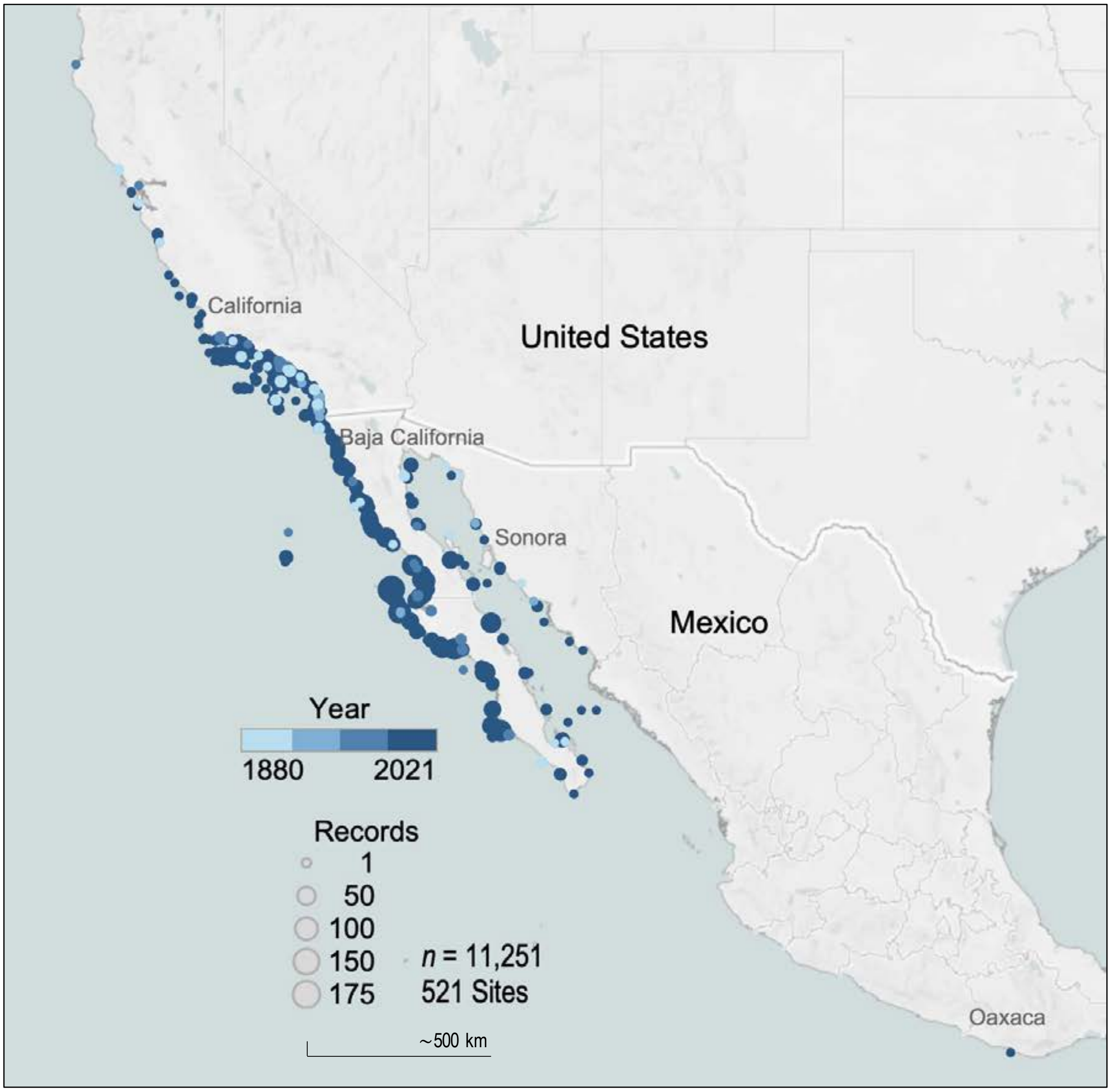

FIGURE S1. Giant sea bass (GSB) geographic distribution map based on 11,251 records from 521 sites across the Northeastern Pacific extracted from the Global Biodiversity Information Facility (gbif.org), California Department of Fish and Wildlife (CDFW), the California Recreational Fisheries Survey (CRFS) (https://www.recfin.org/), the Mexican government fisheries management agency (CONAPESCA), scientific collections(1) in Mexico and the USA, fishery-independent surveys(2), and data from Proyecto Mero Gigante. Seventy-three percent of the GSB distribution is found in Mexican water based on all records shown on the map, except for the larval record in Oaxaca, Mexico. The Oaxaca record represents an isolated record from the next southernmost record for more than 1500 km with no confirmed adult records in between. [GBIF.org (9 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.dfnxsy].

(1) Scientific collections

Scripps Institution of Oceanography (SIO)
Universidad Michoacana de San Nicolás de Hidalgo (UMSNH)
Universidad Autónoma de Baja California (UABC)
Centro de Investigaciones Costeras at Universidad de Guadalajara (U de G)
Centro Interdisciplinario de Ciencias Marinas del IPN (CICIMAR)
Centro de Investigaciones Biológicas del Noroeste (CIBNOR)
National Fish Collection at Universidad Nacional Autónoma de México (UNAM)
Fish collection at ICMYL Mazatlán (UNAM)
Universidad Autónoma de Sinaloa at Mazatlán (UAS)
Centro de Investigación en Alimentación y Desarrollo at Sonora (CIAD Sonora)
Fish Collection at Universidad Autónoma de Nuevo León (UANL)
Fish Collection at Universidad Autónoma de Guerrero (UAGro)
The López-Perez Lab at the Universidad Autónoma Metropolitana (UAM)
Fish Collection at Universidad Autónoma de Nayarit (UAN)
Universidad del Mar at Puerto Ángel, Oaxaca (UMAR)

(2) Fishery independent surveys

Fish surveys from Proyecto Mero Gigante
Fish surveys from the ONG Comunidad y Biodiversidad, A.C. (COBI)
Fish surveys from the Reyes-Bonilla Lab at the Universidad Autónoma de Baja California Sur
Fish surveys from the ONG Ecosistemas y Conservación: Proazul Terrestre A.C.
Fish surveys from Centro para la Biodiversidad Marina y Conservación, A.C. (CBMC)

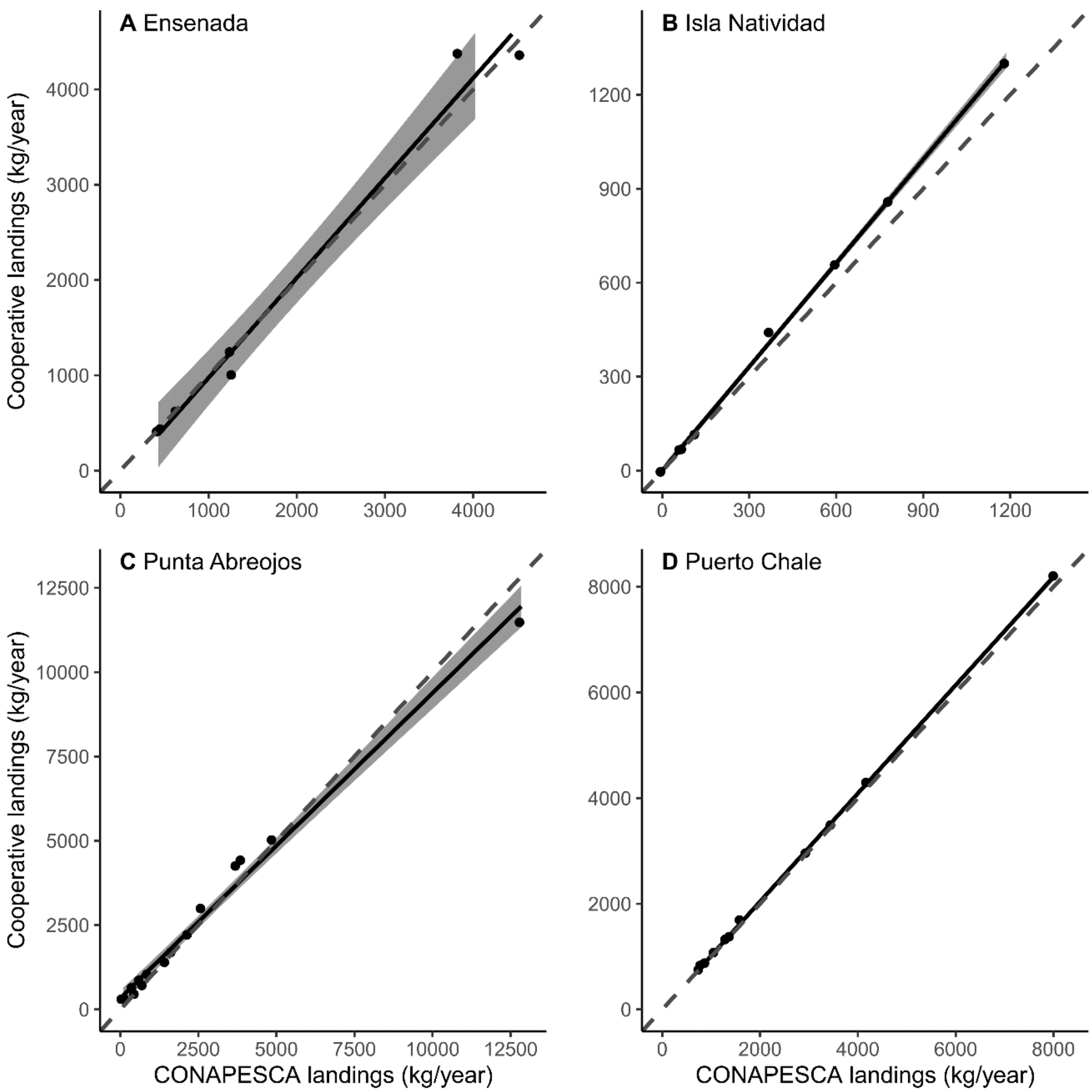

FIGURE S2. Giant sea bass landings data from the Mexican government fisheries management agency (CONAPESCA) do not statistically differ from data gathered directly from four fishing cooperatives. The four fishing cooperatives have an important share in catches, averaging 2-4 tonnes per year.