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The artisanal shark fishery in the Gulf of California: Historical catch reconstruction and vulnerability of shark species to the fishery

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Abstract of the thesis presented by **Luz Erandi Saldaña Ruiz** as a partial requirement to obtain the Doctor of Science degree in Marine Ecology.

The artisanal shark fishery in the Gulf of California: Historical catch reconstruction and vulnerability of shark species to the fishery

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In the Gulf of California artisanal shark fishery detailed historical records by species are not available, therefore, is difficult to evaluate the species and achieve adequate management strategies for this region. In recent years, methods to evaluate the fish populations under a fishery regime with data-poor situations have been developed. One of these methods is the Productivity and Susceptibility Analysis (PSA) that evaluates the vulnerability of a stock to the fishery. To establish a baseline for future evaluations of the populations of the shark species, we reconstructed the Gulf of California shark landings. In addition, the PSA analysis was applied to shark species to evaluate their vulnerability to the artisanal fishery of the Gulf of California. An approach for reconstructing catch time series was used to estimate the total shark landings of the Gulf of California artisanal fishery from 1939 to 2014, and a species composition for a 55-year period (1960 to 2014). And were evaluated the rate at which a species population can recover after a potential fishery depletion (Productivity) and the potential impact of the fishery on the species (Susceptibility). The productivity and susceptibility analysis was made in several workshops with stakeholders in the Gulf of California artisanal shark fishery. The results suggest an increasing trend in the reconstructed shark landings of the artisanal and middle-sized vessel fishery. Thirty-eight shark species were identified in the Gulf of California artisanal fishery. *Mustelus* spp., *Sphyrna lewini, Rhizoprionodon longurio, Squatina californica, Carcharhinus falciformis, Sphyrna zygaena,* and *Carcharhinus limbatus* were the taxa that have maintained high landings of more than five decades. A noticeable decline of *Carcharhinus leucas, Nasolamia velox, Negaprion brevirostris, Sphyrna* spp., *Carcharhinus altimus, Carcharhinus obscurus, Galeocerdo cuvier, Carcharhinus porosus, Triakis semifasciata*, and *Carcharhinus brachyurus* were observed in the estimations. While for *Prionace glauca, Alopias pelagicus*, and *Isurus oxyrinchus* the landings increased. The biological productivity in the analyzed species ranged from low (89% species) to moderate (10.5% species); none of the species resulted with high productivity. The majority of the species (66%) are moderately susceptible to the Gulf of California fishing activities, 12 species (31%) were low susceptible, and only one species, *M. californicus*, is highly susceptible to the fishing activities. The species at high risk to overexploitation were *C. leucas, C. obscurus, C. brachyurus, T. semifasciata, N. brevirostris, N. velox, G. cuvier, C. altimus, C. porosus, G. cirratum, G. galeus, S. media, S. corona, S. tiburo,* and *S. mokarran.* The productivity and susceptibility analysis is an alternative to traditional fishing assessment in fisheries with data-poor situations.

Keywords: Gulf of California, artisanal fishery, sharks, ecological risk assessment, historical catch data reconstruction.

Resumen de la tesis que presenta **Luz Erandi Saldaña Ruiz** como requisito parcial para la obtención del grado de Doctor en Ciencias en ecología marina.

La pesca artesanal de tiburones en el Golfo de California: reconstrucción de sus capturas históricas y la vulnerabilidad de las especies a esta pesquería

Resumen aprobado por:

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Dr. Oscar Sosa Nishizaki
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En la pesquería artesanal del Golfo de California no hay registros históricos por especie, debido a esto no es posible hacer evaluaciones poblacionales que permitan lograr adecuadas estrategias de manejo para esta región. En años recientes se han desarrollado métodos para evaluar poblaciones de peces bajo un régimen de pesquería con datos pobres. Uno de estos métodos es el análisis de productividad y susceptibilidad (PSA), el cual evalúa la vulnerabilidad de un stock a una pesquería. En el presente estudio se reconstruyeron los desembarques de tiburones de la pesca artesanal del Golfo de California para establecer una base para futuras evaluaciones poblacionales de las especies de tiburones. Además, se aplicó un PSA a las especies de tiburones para evaluar su vulnerabilidad a la pesca artesanal del Golfo de California. Se utilizó una aproximación para reconstrucción de series de tiempo de capturas para estimar los desembarques totales de tiburones en el Golfo de California de 1939 a 2014 y la composición específica para un periodo de 55 años (1960-2014). Y fue evaluado el potencial de recuperación de una especie después de un agotamiento potencial por pesca (Productividad) y el impacto potencial de la pesquería a las especies (susceptibilidad). Los resultados sugieren un incremento en las tendencias de los desembarques de tiburones en la pesca artesanal. Treinta y ocho especies de tiburones fueron identificadas en la pesca artesanal del Golfo de California. Los taxa *Mustelus* spp., *Sphyrna lewini*, *Rhizoprionodon longurio*, *Squatina californica*, *Carcharhinus falciformis*, *Sphyrna zygaena*, *y Carcharhinus limbatus* han mantenido altos desembarques de más de cinco décadas. Un notable decremento en las estimaciones es observado para *Carcharhinus leucas*, *Nasolamia velox*, *Negaprion brevirostris*, *Sphyrna* spp., *Carcharhinus altimus*, *Carcharhinus obscurus*, *Galeocerdo cuvier*, *Carcharhinus porosus*, *Triakis semifasciata* y *Carcharhinus brachyurus*. Mientras que se observa in incremento en las estimaciones para *Prionace glauca*, *Alopias pelagicus*, y *Isurus oxyrinchus*. La productividad biológica en las especies analizadas estuvieron en un intervalo de bajo (89% de las especies) a moderado (10.5% de las especies); ninguna de las especies resulto con productividad alta. La mayoría de las especies (66%) resultaron ser de susceptibilidad moderada a las actividades de la pesca artesanal del Golfo de California, 12 especies (31%) fueron de susceptibilidad baja y solo una especie, Mustelus californicus, resultó con susceptibilidad alta. Las especies con un alto riesgo a la sobreexplotación fueron *C. leucas*, *C. obscurus*, *C. brachyurus*, *T. semifasciata*, *N. brevirostris*, *N. velox*, *G. cuvier*, *C. altimus*, *C. porosus*, *G. cirratum*, *G. galeus*, *S. media*, *S. corona*, *S. tiburo* y *S. mokarran*. Las tendencias de los desembarques históricos. El análisis de productividad y susceptibilidad es una alternativa a las evaluaciones pesqueras tradicionales para pesquerías con datos pobres.

Palabras clave: Golfo de California, pesquería artesanal, tiburones, análisis de riesgo ecológico, reconstrucción histórica de capturas.

Dedication

Esta tesis está dedicada a mis abuelos, los cuales ya no están conmigo pero sé que estarían orgullosos.

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Chapter 1. Introduction

Ecological data sets rarely extend back more than a few decades, limiting our understanding of environmental changes and its drivers (Thurstan et al., 2015). This is not different for several shark fisheries records worldwide. Detailed records of the history of the exploitation of shark populations in the Gulf of California are not available, jeopardizing their assessment and management.

Sharks have a long history of exploitation in the GC, with landings starting around 1870 in Mazatlán, Sinaloa, (Applegate et al., 1993), and has been a traditional activity for Mexican fishermen (Applegate et al., 1979). Since the end of the 1800's, shark products as fins, meat, skin, liver oil (for obtaining vitamin A and lubricants), and teeth (sold as handicrafts) have had an important role in the Mexican fishing economy (Ferreira, 1958). Because of the low value of their meat, sharks also have had an impact on coastal communities, has been sources of jobs and low value food protein (Castillo-Géniz et al., 2008). Sharks are widely consumed fresh, especially small sharks known as cazón, in rural areas, with an increasing demand from large city markets at Mexican high lands (Rose, 1998; Castillo-Géniz et al., 2008). The worldwide increase of shark catches has been slower when compared with other fisheries, because these organisms have a low commercial value and low abundances compared with teleost fishes populations (Bonfil, 1994). The life history patterns of most of the sharks have been characterized as having low fecundity, slow growth, late maturity, long gestation periods and large longevity, that results in slow growth rates and therefore may have a slow recovery of their populations after an intense fishing effort (Bizzarro et al., 2007; Camhi et al., 1998; Musick, 1999).

According to the Food and Agriculture Organization (FAO) statistics, total worldwide shark catches reached 550,355 mt in 2013, and Mexico was among of the seven countries that produce half of the total catches (FAO, 2014). In Mexico, the shark fishery occupies the 9th place in the total national fish production, reaching to 27 thousand tons in 2013. Sixty two percent (16,693 mt) of these shark catches were produced in the Pacific coast of Northwestern Mexico (SAGARPA, 2002-2013), where the Gulf of California (GC) is located, and where fishing on sharks was developed since the end of the 19th century (Bonfil, 1994; Ferreira 1958). The shark fishery in the GC is conducted by two officially recognized fishing units: the Medium Scale fishery with vessel size of 10 to 27 m in length; and the Small Scale or Artisanal Fishery, with vessels with less than 10 m of length (DOF, 2007; Bizzarro et al., 2007). A high percentage of the shark catch comes from the artisanal fishery, so this activity has a high socio-economic value in the GC region (Pérez-Jiménez et al., 2005). In this region the artisanal fishery has a multi-specific composition of its catch due to the diversity of shark species distributed in the gulf. Also, this fishery is characterized because use multiple fishing gears, like bottom and surface set gillnets, bottom and surface longlines and occasionally handlines (Bizzarro et al., 2007; Bonfil, 1994).

Despite the importance of shark fisheries at global, national and regional levels, the biological and fishing information for this group is still poor in several countries (Bonfil, 1994). In the 2011 FAO catch statistics for chondrichthyans, which includes sharks, only the 38% of the catches were identify to a species level, and up to 34% were recorded as sharks and rays without more specifications (FAO, 2012). Mexican official shark catch statistics have several caveats as they are reported only as two categories, depending of the size of the sharks: “Cazón” for small sharks, less than 150 cm of total length (TL), and “Tiburon” for large sharks with lengths larger than 150 cm of TL. This ambiguous situation has jeopardized the understanding of the trends of shark catches at species level, and the assessment of the shark populations under fishing exploitation (Bonfil, 1994; Castillo-Géniz, 1992).

In February of 2007, the Mexican government enacted a set of official standards, NOM-029-PESCA-2006, to improve the management of sharks and rays (DOF, 2007), with the objective to attain a sustainable shark fishing level across the country, and to improve the catch records. These standards established an official logbooks system for shark and rays fisheries, which requires the recording of the species composition of the catch for each fishing trip, as well as other information related with the fishing gear. This system has produce official statistics by species that are reported by fishermen at each of the Official Offices of the National Commission for Fisheries and Aquaculture (CONAPESCA) and posted in the web site of this commission (CONAPESCA, 2016). Nevertheless, these official shark statistics still have several deficiencies: 1) shark species are recorded by common names, with a mixing of local names; 2) there is no differentiation of catches between artisanal and medium scale fisheries; and 3) the information is available only for a recent period (2006-2012).

In some regions of the Mexican Pacific a decline trend of shark landings has been reported, interpreted as a result of an intensive and poorly regulated fishing pressure (Ramirez Amaro et al., 2013). However, no formal assessments of the shark populations status have not been produced mainly due to the lack of landing and fishing effort time series (Pérez-Jiménez and Mendes-Loeza, 2015). To evaluate populations of the shark species caught in the GC requires extensive data, such as time series result of long-term monitoring of the fishery and extensive information on biological and selectivity of fishing gear (Hoff and Musick, 1990; Walker, 2005). A sustainable management of this group is difficult due to the lack of accurate and detailed information to determine the effects of fishing on populations of shark species caught (Bonfil,1997, Márquez–Farías, 2002), especially in a complex fishery as the artisanal fishery in the

GC. It is therefore necessary to apply a different approach to address the assessment of this fishery, in this context, the Ecological Risk Assessment of the Effect of Fishing (ERAEF) is a methodology used to evaluate the effect of the fishing activities in the species and is special for data-limited fisheries (Hobday et al., 2004, Astles et al., 2006). One of the tools of this methodology is the Productivity and Susceptibility Analysis (PSA), this semi-quantitative analysis quickly evaluates the vulnerability of species to fishing (Hobday et al., 2011).

In this study I reconstructed the historical landings in the GC for the period of 1939 to 2014, for the artisanal fishery middle-size vessel fishery landings for the 1988 to 2014, and the shark species composition of the landings for the period 1960 to 2014. I extensively reviewed the available catch records and historical descriptions of the fishery in the formal and grey literature to produce the landing time series following a recently developed approximation to reconstruct catches by country (Chapter 2). Also I estimated the relative vulnerability to fishing for each of the shark species in the GC, through a PSA analysis that allows the identification of species with a higher risk fishery impact. This study addresses the following questions for the shark species in the artisanal fishery in the GC: 1) How was the historic composition of the fishery? 2) How are the trends of the catches? 3) How is the productivity of the shark species? 4) How is the susceptibility of the shark species? 4) How is the vulnerability of the shark species to the fishery?

1.1. Justification

The Gulf of California is one of the most historically important regions in Mexico for shark fisheries. However, detailed historical shark landings are not available, making it difficult to plan adequate management strategies. To establish a baseline for future research and assessments, this study attempts to analyze historical trends in GC shark fishery landings in a data-poor environment.

In recent years, methods to evaluate the fish populations under a fishery regime with data-poor situations, like the Gulf of California artisanal fisheries, have been developed. One of these methods is the Productivity and Susceptibility Analysis (PSA) that evaluates the vulnerability of a stock to the fishery. This rapid risk assessment can be applied to evaluate the vulnerability of the species to the fishery. In this analysis we evaluated the capability of a species to recover after potential depletion (Productivity) and the potential impact of the fishery on the species (Susceptibility). The PSA is an alternative to conventional fisheries stock assessment methods when a data-poor situation is presented. This analysis provides guidelines to prioritize research.

1.2. Hypothesis

The catch composition of the artisanal shark fishery in the Gulf of California it has not changed in the last three decades.

All shark species are going to have low productivity due their life history characteristic of low fecundity, slow growth, late maturity and longevity.

All the shark species are going to have high susceptibility to the fishery due to a large overlap of the fishing activities with the distribution of the species.

The relative vulnerability of all the shark species to the artisanal fishery in the Gulf of California will be medium to high due to their low biological productivity and high susceptibility to the fishery activities.

The shark species with high historical catches estimated are going to have high relative vulnerability to the artisanal fishery in the Gulf of California.

1.3 Objectives

1.3.1 Main objective

Estimate the catch composition of the artisanal shark fishery in the Gulf of California and determine the relative vulnerability of shark species to the fishery through an historical reconstruction of catches and an analysis of Productivity and Susceptibility, to improve the fishery data and identify the species with high relative vulnerability to the fishery.

1.3.2 Specific objectives

Collect and review the historical data of the fishery and biological aspects of the shark species caught in artisanal fisheries in the Gulf of California through the construction of a database that includes information by species, region and historical aspects of the shark fishery.

Estimate the historical catch composition of the artisanal shark fishery in the Gulf the California for the period from 1939 to 2014 by using official catch records and qualitative and quantitate descriptions of the landings of the artisanal shark fishery.

Evaluate the biological productivity of the shark species in the Gulf of California through the revision of their life history traits.

Evaluate the susceptibility of the shark species to the artisanal fishery by analyzing their interaction to the fishing activities.

Assess the relative vulnerability of the shark species to the artisanal fishery in the Gulf of California through their evaluation of the biological productivity and their susceptibility to the fishery.

Perform a sensitivity analysis to the PSA to observe the behavior of the outputs by varying inputs parameters.

Integrate the historical catch estimations and the vulnerability of the species resulting to identify the main gaps in information and the shark species with urgent needs of more robust assessments.

Chapter 2. Historical reconstruction of Gulf of California shark fishery landings and species composition, 1939 to 2014, in a data-poor fishery context

2.1. Introduction

Most shark species have been described as vulnerable to overfishing because of their unique life history characteristics, which include low fecundity, slow growth, late age at maturity and long lifespan (Musick, 1999; Stevens et al., 2000). Sustainable management of shark fisheries has been recognized as a global priority to ensure the conservation of commercially harvested sharks. However, typical parameters used in shark fishery management require adequate fishery data, including catch and effort statistics and species composition information (Punt et al., 2000). The lack of such data has jeopardized the assessment of shark populations, particularly in developing countries such as Mexico.

Mexico is the world´s sixth-largest producer of shark fishery products (Dent and Clark, 2015). More specifically, northwestern Mexico is the most important region in the country for shark fisheries, accounting for 62% (17,615 metric tons) of total shark landings (SAGARPA, 2015). Two types of shark fisheries operate in this region: the artisanal fishery, composed of <10 m length vessels with outboard engines known as 'pangas' (Holts et al., 1998); and the middle-sized vessel fishery, composed of industrial longline fishing boats, 10-27 m in length, that mainly target pelagic sharks (DOF, 2007). In Mexico, artisanal fisheries account for about 97% of the marine fleet (Fernández et al., 2011).

An area of special biological significance in northwestern Mexico is the Gulf of California (GC), a highly productive sea with great biodiversity, that has been recognized as the most important fishing region in Mexico (Lluch-Cota et al., 2007), and designated as a Large Marine Ecosystem (Sherman, 1994). Shark fishing became important in the GC during World War II, when large shark species were targeted to provide shark liver oil to the United States as sources of vitamin A (McGoodwin, 1976; Applegate et al., 1979). This fishery has since evolved into a multi-species, multi-gear fishery with high socio-economic value (Castillo-Géniz et al., 1998; Holts et al., 1998; Sosa-Nishizaki, 2008; Cartamil et al., 2011).

To improve management of the GC shark fishery, and to understand the potential vulnerability of harvested species, it is necessary to identify species-specific landing trends through time (Camhi et al., 1998; Musick, 1999; Bizzarro et al., 2007). Unfortunately, incomplete documentation of GC shark fishery landings limits our understanding of historical trends. The available official landing records have three major deficiencies. First, historical shark landings records are not available for some years. Second, species composition data are lacking. And third, there is no differentiation between the landings from the artisanal and the middle-sized vessel fisheries.

Several previous studies have highlighted the importance of using of all available fishery data, as well as qualitative information, to estimate and reconstruct historical fisheries landings (Pauly, 1998; Zeller et al., 2007; Harper et al., 2014; Leitão et al., 2014). Reconstruction of landings time series in data-poor situations requires interpolations and bold assumptions (Zeller et al., 2006). Although imperfect, reconstruction of past landings and species composition can provide a reasonable approximation of changes in marine fisheries over time, and help elucidate the current status of shark populations (Pauly, 1998). Thus, this information is fundamental to evaluating the effectiveness of current management.

In light of the ecological importance of the GC and the magnitude of its shark fisheries, this study attempts to analyze historical trends in GC shark fishery landings in a data-poor environment. Based upon an exhaustive review of extant literature and alternative data sources, we have reconstructed total shark landings from GC shark fisheries for the period 1939 to 2014, species composition of the landings for the period 1960 to 2014, and assessed the uncertainty inherent in our data sources and subsequent analyses. We discuss the history of GC shark fisheries, and implications for management of sustainable shark fisheries in the GC.

2.2 Methods

2.2.1 Study Area

The GC is a semi-enclosed sea in the eastern North Pacific Ocean. It is located between the eastern coasts of the Mexican states of Baja California (BC) and Baja California Sur (BCS), and the western coasts of Sonora (SON), Sinaloa (SIN), and Nayarit (NAY) (Figure 1). This study considers the southern limit of the GC as a line connecting Cabo San Lucas (BCS) and Cabo Corrientes (Jalisco), a delineation based on faunal and oceanographic features, and Mexican official marine territorial planning (Roden, 1964; Brusca et al., 2005; DOF, 2006; Álvarez-Borrego, 2010). The GC is 1130 km long, ranges in width from 80 to 209 km, with an area of approximately 200,000 km^2, and reaches depths greater than 3000 m (Lluch-Cota et al., 2007). Due to overfishing and resource sustainability concerns, the GC is closely monitored by conservation groups (Lluch-Cota et al., 2007; Álvarez-Romero et al., 2013).

Dynamic oceanographic processes of the GC include gyres, fronts and upwellings, that produce elevated sea surface temperature variability and primary productivity (mostly in the north and central zones) during winter and spring (Álvarez-Romero et al., 2013). The GC has three natural fertilization mechanisms: wind-induced upwellings, tidal mixing, and thermohaline circulation. (Álvarez-Borrego, 2010). In winter conditions (December–May), upwellings occur off the eastern coast of the GC with northwesterly winds, and off the BC coast with southeasterly winds in summer conditions (July–October). These upwellings and gyres increase the phytoplankton communities (Álvarez-Borrego, 2010; Santamaría-del-Ángel et al., 1994). These processes allow the GC to support a great diversity of sharks and other ichthyofauna, which in turn support several commercial fisheries (Lara-Lara et al., 2008; Álvarez-Romero et al., 2013). For example, Hastings et al. (2010) reported 87 species of cartilaginous fish within the GC, and around 72 species (83%) are caught in the GC artisanal fishery (Bizzarro et al., 2007). Fish diversity is higher in southern latitudes of the GC, due to elevated temperatures, greater habitat diversity, and increased connection with Pacific waters (Lehner, 1979; Álvarez-Borrego, 2010; Brusca et al., 2005).

2.2.2 Reconstruction of GC total shark landings: 1939 to 2014

This study attempts to reconstruct total GC shark landings during the period 1939 to 2014 using a variety of available data sources. In addition, we estimate species composition for the artisanal fishery catch from 1960 to 2014, and assess the uncertainty associated with our analyses. Reconstruction of total landings and species composition followed the approach of Harper et al. (2014), Zeller et al. (2007; 2015), and fundamentals for reconstructing catch time series of Pauly (1998).

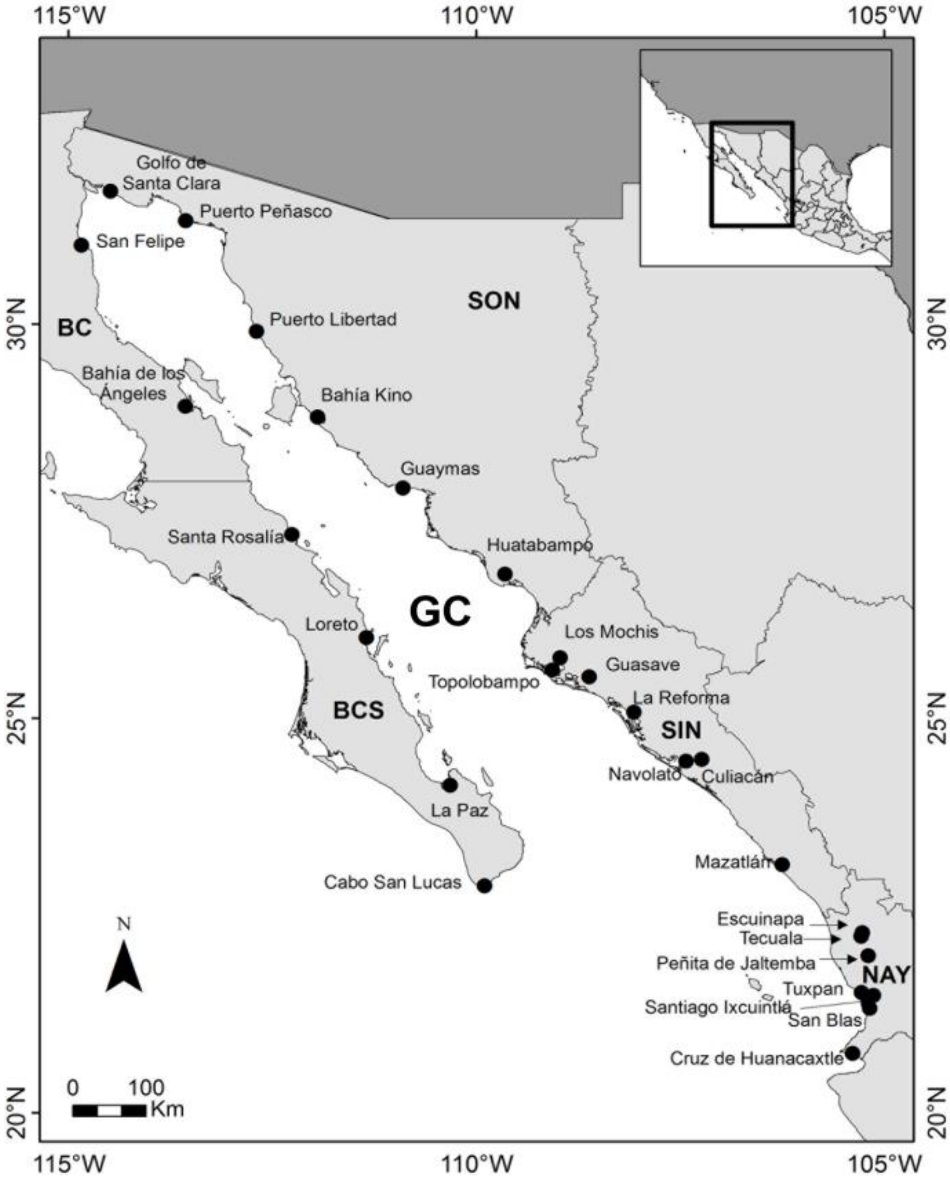


Figure 1. Gulf of California region (GC). Black dots indicate the 26 local fishery offices referenced in the study. BC: Baja California; BCS: Baja California Sur; SON: Sonora; SIN: Sinaloa and NAY: Nayarit.

2.2.3 Data sources

Details of all data sources used in this study are reported in Table 1. The baseline data used for the reconstruction consist of Mexican official landings statistics that have been compiled since 1940 by several agencies of the Mexican Federal Government (Arreguín-Sánchez and Arcos-Huitron, 2007). This process begins with fishery permit holders, who regularly submit landing slips to local fishery offices (FOs) of the Mexican National Commission of Fisheries and Aquaculture (CONAPESCA). FOs are typically located at major ports or close to important fishing communities (Escobar-Fernandez, 1989). Landing data are then compiled at CONAPESCA's central office, and reported annually through the Fisheries Statistics Yearbook (Anuario Estadístico de Pesca), which includes landings in dressed (i.e., headed and gutted) weight and rounded weight (kg) by species or species group for each state (Secretaría de Marina, 1940-1969; Departamento de Pesca, 1979-1981; Secretaría de Pesca, 1982-1994; Secretaría del Medio Ambiente, Recursos Naturales y Pesca, 1995-2001; Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, 2002-2015). For this study we used only rounded weight. Yearbooks do not report shark catch by species, and shark landings have historically been reported under two categories: "Tiburon" [sharks >150 cm TL (Total Length)] and "Cazon" (sharks ≤150 cm TL). To generate historic total shark landings series for each state, both categories were pooled, and are referred to hereafter as total shark landings (TSL), expressed in metric tons (t).

Table 1. Main sources used for the historical reconstruction of Gulf of California (GC) shark fishery landings, and species composition. The data available by fishery offices (FOs) and from Baja California (BC), Baja California Sur (BCS), Sonora (SON), Sinaloa (SIN), and Nayarit (NAY) is specified. The periods of each data type are indicated chronologically.

Data type	Period	Reference	Description
Mexican official landings statistics	1939-1950	Secretaría de Marina, 1940-1960	Shark catches by regions*
	1951-1960	Secretaría de Marina, 1952-1961	Shark catches by regions*
	1952, 1954 and 1957	Secretaría de Marina, 1952, 1954 and 1957	Shark catches by FOs
	1961-1969	Secretaría de Marina, 1962-1970	Only total shark landings available
	1970-1976	Historical landings reported in SEMARNAP, 1999	Only total shark landings available
	1977-1980	Departamento de Pesca, 1979-1981	Shark catches in rounded weight by FOs
	1981-1982	Secretaría de Pesca, 1982-1984	Shark catches in rounded weight by FOs
	1983-1991	Secretaría de Pesca, 1985-1992	Only total shark landings by state available
	1992	Secretaría de Pesca, 1994	Shark catches in rounded weight by FOs
	1993-2000	SEMARNAP, 1995-2001	Shark catches in rounded weight by FOs
	2001-2014	SAGARPA, 2002-2015	Shark catches in rounded weight by FOs
Diverse literature (Journal articles, fishery survey reports, gray literature, and management documents) used in the species composition estimations	1934-1969	Hernández-Carvallo, 1971	Shark fishery in Mexico
	1961-1965	Ramirez Hernandez and Arvizu Martinez, 1965	Species catalogue from BC
	1962-1965	Kato and Hernandez Carvallo, 1967	Shark tagging in the eastern Pacific
	1964	Kato, 1965	Artisanal shark fishery in Mazatlán, SIN
	1970s	Castro-Aguirre, 1978	Species catalogue

1970s	Applegate, 1979	Shark species descriptions
1972	Taylor and Castro Aguirre en 1972	Species description
1975	Olguín-Quiñones, 1975	Marine fishes catalogue from Mexico
1978-1982; 1983	Castro-Aguirre and Balart ,1997	Species catalogue
1978-1993	Balart et al., 1995	Description of species
1981-1986	Abitia-Cardenas et al., 1994	Species list from Bahia de la Paz, BCS
1981-1982	Díaz et al., 1982	Artisanal shark fishery in SIN
1981-1982-1984	Galván-Magaña et al., 1989	Artisanal shark fishery in the GC
1980s	Compagno, 1984	Species catalogue
1980s	Castillo-Géniz, 1992	Shark fisheries in Mexico
1985-1990	Rodríguez De La Cruz et al., 1994	Fisheries in México
1986-1987	Mendizábal and Oriza, 1995	Biology study
1986-1988-1989	Klimley et al., 1993	Behavior study
1987-1988	Saucedo Barron and Ramírez Rodríguez, 1994	Artisanal shark fishery in SIN
1990s	Fischer et al., 1995	Species catalogue
1990s	Castillo-Géniz et al., 1996	Shark fisheries in Mexico
1990s	Arenas y Díaz de León, 2000	Artisanal shark fishery in SIN
1990-1992-1993	Galván-Magaña et al., 1996	Species catalogue
1990-1996	Guerrero Maldonado, 2002	Artisanal shark fishery in the GC
1990-1996	Alonso Castelan, 1999	Artisanal shark fishery in BCS
1995	Bellido Millán and Villavicencio Garayzar, 2000	Artisanal shark fishery in the GC
1995-1996	Furlong-Estrada and Barragan-Cuencas, 1997	Artisanal shark fishery
1996	Cudney-Bueno and Turk-Boyer, 1998	Artisanal fishing in the Upper GC
1996-2008	Salomón-Aguilar et al., 2009	Shark breeding grounds studies
1997-1998	Castillo-Géniz et al., 2000	Artisanal shark fishery in the GC
1997-1998	Campos Dávila et al., 2005	Gillnet fishery
2000-2005	Díaz-Uribe et al., 2013	Artisanal shark fishery
2003-2004	Santana Morales et al., 2004	Chondrichthyes catalogue
2003-2004	Pérez-Jiménez and Sosa-Nishizaki, 2008	Reproductive biology studies
2000s	Espinosa-Pérez et al., 2004	Species catalogue
2000s	CONAPESCA-IPN, 2004	Management document
2000s	DOF, 2007	Management document
2004	Galeana-Villaseñor et al., 2008	Shark fishery
2004-2006	Mejía Salazar, 2007	Reproductive biology studies
2005-2009	Corro-Espinosa et al., 2011	Reproductive biology studies
2007-2010	Gallegos-Camacho and Tovar-Ávila, 2011	Biology studies
2010s	INAPESCA, 2012	Management document

Species composition of Gulf of California artisanal shark fishery	1998-1999	Smith et al., 2009	BC shark fishery species composition
	1998-1999	Bizzarro et al., 2009a	SON shark fishery species composition
	1998-1999	Bizzarro et al., 2009b	BCS shark fishery species composition
	1998-1999	Bizzarro et al., 2009c	SIN shark fishery species composition
	1997-1999	Villavicencio-Garáyzar, 2000	SON shark fishery species composition
	1999-2000	Márquez-Farías, 2000	SON shark fishery species composition
	1995-1996; 2000-2001	Pérez Jiménez et al., 2005	NAY shark fishery species composition
	2007-2011	Mondragón Sánchez, 2011	NAY shark fishery species composition

*Region one included the states of Baja California, Baja California Sur, Sonora, Sinaloa, and Nayarit.

Total shark landings for the GC (TSL-GC) were compiled from official yearbook statistics recorded at 26 local FOs from the five states bordering the GC (Table 1). In the case of BC and BCS (states with both Pacific and GC coasts), only records from the six FOs on the GC coast were used (Figure 1). However, official catch statistics contain data gaps (missing years of FOs data), requiring the reconstruction of an estimated TSL-GC for each type of fishery (artisanal and middle-sized vessel), and for several time periods, each with unique characteristics and requiring different analytical approaches and assumptions, as described below:

2.2.3.1 Artisanal Fishery

a) 1939-1950: Shark liver was the main product during this period due to high demand for vitamin A during World War II, with most of the meat discarded (Hernández-Carvallo, 1971; Alcalá-Moya, 1999). Shark landings during this period were reported only in terms of liver weight (Secretaría de Marina, 1940-1969), which was converted to rounded weight using an FAO conversion factor of 8.13 (Vannuccini, 1999).

b) 1951 to 1960: Shark meat becomes the main shark fishery product due to the advent of synthetic vitamin A production (Ferreira, 1958; Hernández-Carvallo, 1971). For BC and BCS, all landings reported before 1960 were assumed to correspond to GC fishing efforts, because Pacific coast fisheries did not begin until the early 1960s (Alcalá-Moya, 1999).

c) 1961-1976: During this period, TSL was reported only for the entire country. To estimate landings from the GC only, we used the relative proportions (72%) of TSL-GC to TSL found in the first available regional data (1977-1979), assuming a similar fishing dynamic.

d) 1977-1982: Shark landings reported by FOs located in the GC coast (for BC and BCS), and landings by state (SON, SIN, and, NAY) were used as TSL-GC.

e) 1983-1991: Only TSL records by state (no FO records) were available for this period. To obtain the GC landings from BC and BCS, we used the average percentage of landings reported for GC coast FOs at BC and BCS during 1981-1982, 1992-1993 (40 and 74%, respectively), assuming a similar fishing dynamic.

f) 1992-2014: Shark landings reported by FOs located in the GC coast (for BC and BCS), and landings by state (SON, SIN, and, NAY) were used as TSL-GC.

2.2.3.2 Middle-sized Vessel Fishery

A middle-sized vessel fishery has operated in the GC (based at the port of Mazatlan, SIN) since 1988, primarily targeting pelagic sharks (unpublished data, Villaseñor Talavera [CONAPESCA]). All landings reported at the Mazatlan FO since 1988 pertain to the middle-sized vessel fishery. GC middle-sized vessel shark landings are presented in Figure 2, and these records were subtracted from the TSL-GC to obtain the artisanal fishery catch.

2.2.4 Estimated species composition of the GC artisanal shark fishery, 1960-2014

Species composition of the GC artisanal shark fisheries was reconstructed based upon a comprehensive literature review (Table 1) that included journal articles, fishery survey reports, gray literature (including technical reports and academic theses), and management documents. Data availability was too sparse prior to 1960 to include in analyses. In certain cases where accurate species identification was uncertain, sharks from the genera *Mustelus* and *Sphyrna* were pooled into species groups (Bizzarro et al., 2009a). *Mustelus* spp. included *M. californicus, M. henlei, M. lunulatus*, and *M. albipinnis. Sphyrna* spp. included

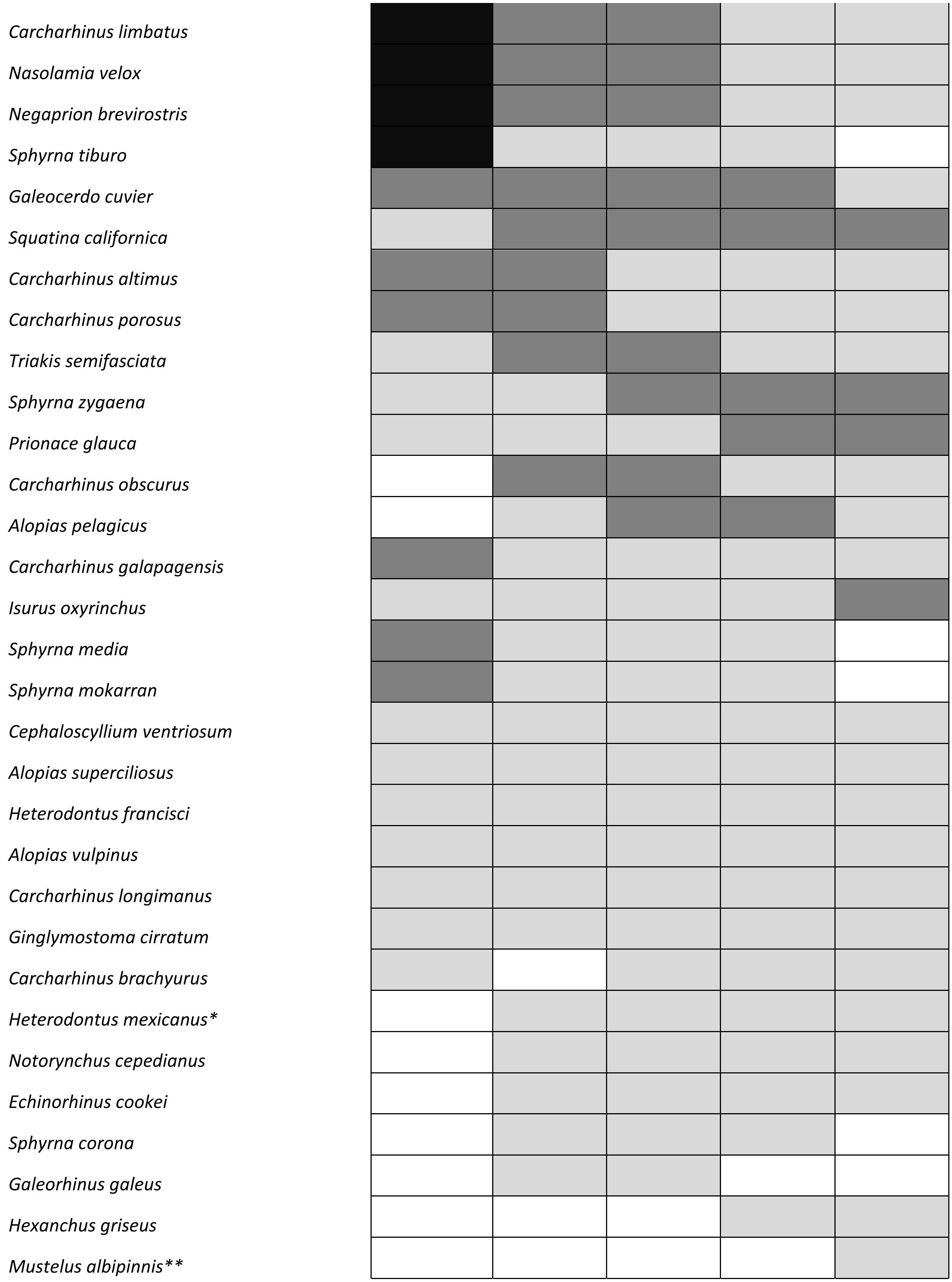
S. lewini, *S. zygaena*, *S. mokarran, S. tiburo, S. corona,* and *S. media*. Where unambiguous identification was possible for *S. lewini* and *S. zygaena*, these data are reported separately.

2.2.4.1 Data and Preliminary Categorization

To graphically illustrate shark species composition and relative importance for each of the five decades from 1960 to 2010, a table was created (Table 2) based upon descriptions of relative abundance found in the literature. Each species was arbitrarily assigned to a qualitative category: 'High' (high frequency in landings), 'Moderate' (intermediate importance), 'Low' (occasionally captured, or classified as bycatch only), or 'No Record'. An annual time series of landings for each shark species during the period 1960 to 2014 was created using a novel combination of both quantitative and qualitative data. Because TSL-GC was known or estimated for each year (see section 2.2.1), a proportion of TSL-GC was assigned to each species for each year. These proportion values were obtained from site-specific quantitative data in the literature from the 1990s (Villavicencio-Garayzar, 2000; Pérez-Jiménez et al., 2005; Bizzarro et al., 2009a, b, c; Smith et al., 2009; Mondragón Sánchez, 2011), the decade with the highest amount of quantitative data. 1990s data were divided into 'low', 'moderate', and 'high' qualitative categories based on their proportional contribution of each species to total landings. The mean of the proportion values of each category were extrapolated to decades with only qualitative information, and the totals for each decade were scaled to 100%, or 1.0.

Table 2. Qualitative abundance rankings for shark species landed in the Gulf of California artisanal fishery. Four categories are indicated: High, Medium and Low relative abundance, and No Record. Species are organized by decade and from High to No record category in descending order.

Species	**Decades**				
	1960's	1970's	1980's	1990's	2000's
Sphyrna lewini					
Rhizoprionodon longurio					
Carcharhinus falciformis					
Mustelus californicus					
Mustelus lunulatus					
Mustelus henlei					
Carcharhinus leucas					


Carcharhinus limbatus
Nasolamia velox
Negaprion brevirostris
Sphyrna tiburo
Galeocerdo cuvier
Squatina californica
Carcharhinus altimus
Carcharhinus porosus
Triakis semifasciata
Sphyrna zygaena
Prionace glauca
Carcharhinus obscurus
Alopias pelagicus
Carcharhinus galapagensis
Isurus oxyrinchus
Sphyrna media
Sphyrna mokarran
Cephaloscyllium ventriosum
Alopias superciliosus
Heterodontus francisci
Alopias vulpinus
Carcharhinus longimanus
Ginglymostoma cirratum
Carcharhinus brachyurus
Heterodontus mexicanus*
Notorynchus cepedianus
Echinorhinus cookei
Sphyrna corona
Galeorhinus galeus
Hexanchus griseus
Mustelus albipinnis**

Relative abundance of the species in the landings

High	Moderate	Low	No record

*This species was not described until 1972 (Taylor and Castro-Aguirre, 1972)

**This species was not described until 2005 (Castro-Aguirre et al., 2005)

2.2.5 Uncertainty

Uncertainty associated with the historical reconstruction was assessed using a scoring process developed by Zeller et al. (2015), and based on uncertainty criteria used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010), with an added criterion (Table 3). The scoring process utilized a workshop with five review participants and an overall score was calculated from the mean of the reviewer's scores for each period. Scores of (1) 'very low', (2) 'low', (3) 'high' and (4) 'very high' were used to evaluate the quality of the time series based on the uncertainty in the data sources, assumptions and methods used for each period and fishing sector of the reconstruction. These scores directly translate into estimated confidence intervals as shown in Table 3. For the TSL-GC reconstruction the scored periods were: 1939-1950, 1951-1960, 1961-1969, 1970-1976, 1977-1982, 1983-1991, 1992-2014, and 1988 to 2005 and 2006-2014 for the middle-sized vessel shark fishery. For the historical species compositions estimation, periods were scored by decades (e.g., 1960s, 1970s, 1980s, 1990s, 2000s and 2010-1014), and for all the species as a group. Confidence intervals were displayed in the mid-year of each scored period (i.e., 1944, 1955, 1965, 1973, 1979, 1987, and 2002 for TSL-GC reconstruction, and 1996 and 2010 for middle-sized vessel shark fishery).

Table 3. Scoring criteria for evaluating the quality of time series of reconstructed catches and assigning confidence intervals.

Score	Confidence interval ± %	Corresponding IPCC criteria*	Historical species composition estimation criteria
4 Very high	20	High agreement and robust evidence	Quantitative species composition descriptions
3 High	30	High agreement and medium evidence or medium agreement and robust evidence	Surveys and studies of the GC shark fishery description
2 Low	50	High agreement and limited evidence or medium agreement and medium evidence or low agreement and robust evidence	Studies only for one region of the GC
1 Very low	90	Low agreement and low evidence	Studies in which the region is not specified (e.g. General list of shark species in Mexico without a description of a specific geographic region)

* Intergovernmental Panel on Climate Change (IPCC) criteria of Mastrandrea et al. (2010), note that 'confidence increases' (and hence confidence intervals are reduced) 'when there are multiple, consistent independent lines of high-quality evidence'

2.3. Results

2.3.1 Reconstructed total shark landings of the Gulf of California fisheries

The reconstructed TSL-GC for the 1939-2014 period had two notable increases, peaking in 1942 (8,910 t) and 1979 (17,581 t), and three notable declines in 1951 (90 t), 1987 (6,989 t) and 1994 (4,750 t) (Figure 2). Artisanal fishery shark landings (1998-2014) were relatively stable throughout the period 1995 to 2011, followed by an increase in 2014. Middle-sized vessel landings (1998-2014) increased to a maximum of 5,054 mt in 2007, and averaged 3,101 mt (Figure 2).

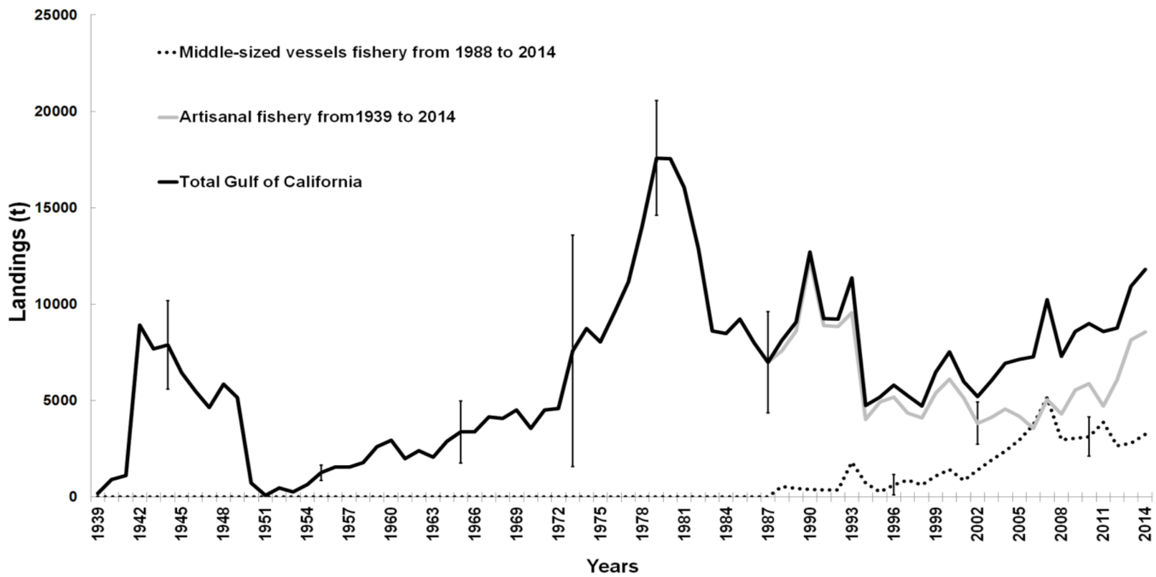


Figure 2. Reconstructed Gulf of California shark landings from 1939 to 2014, with estimated confidence intervals. Continuous black line indicates total shark landings from 1939 to 1975; continuous grey line indicates total artisanal shark fishery landings (prior to 1987, artisanal landings = total landings); and dotted black line indicates middle-sized vessel fishery landings from 1988 to 2014.

2.3.2 Species composition and qualitative categorization

In our historical reconstruction of the GC artisanal and middle-size vessel fishery landings a total of 38 shark species were documented (Table 4). Several of these species (e.g., *S. lewini, Rhizoprionodon longurio, M. californicus,* and *M. lunulatus*) have been consistently dominant in landings since the 1960s (Table 2). However, a relative decline in landings was noted for *Carcharhinus leucas, Carcharhinus limbatus, Nasolamia velox, Negaprion brevirostris*, *Sphyrna tiburo, Galeocerdo cuvier, Carcharhinus altimus, Carcharhinus porosus, Carcharhinus galapagensis, S. media,* and *S. mokarran*. In contrast, some species exhibited a relative increase in landings (e.g., *Carcharhinus falciformis, M. henlei, Sphyrna zygaena, Prionace glauca,* and *Isurus oxyrhinchus*) (Table 2). Other species described in the fishery, but with lower relative frequency in the landings are: *Cephaloscyllium ventriosum*, *Alopias superciliosus, Heterodontus francisci, Alopias vulpinus, Carcharhinus longimanus,* and *Ginglymostoma cirratum* (Table 2). Rarely observed were the species *Carcharhinus brachyurus, Heterodontus mexicanus, Notorynchus cepedianus, Echinorhinus cookei, Sphyrna corona, Galeorhinus galeus, Hexanchus griseus,* and *M. albipinnis* (Table 2). Several of these latter species are not described in some years (Table 2).

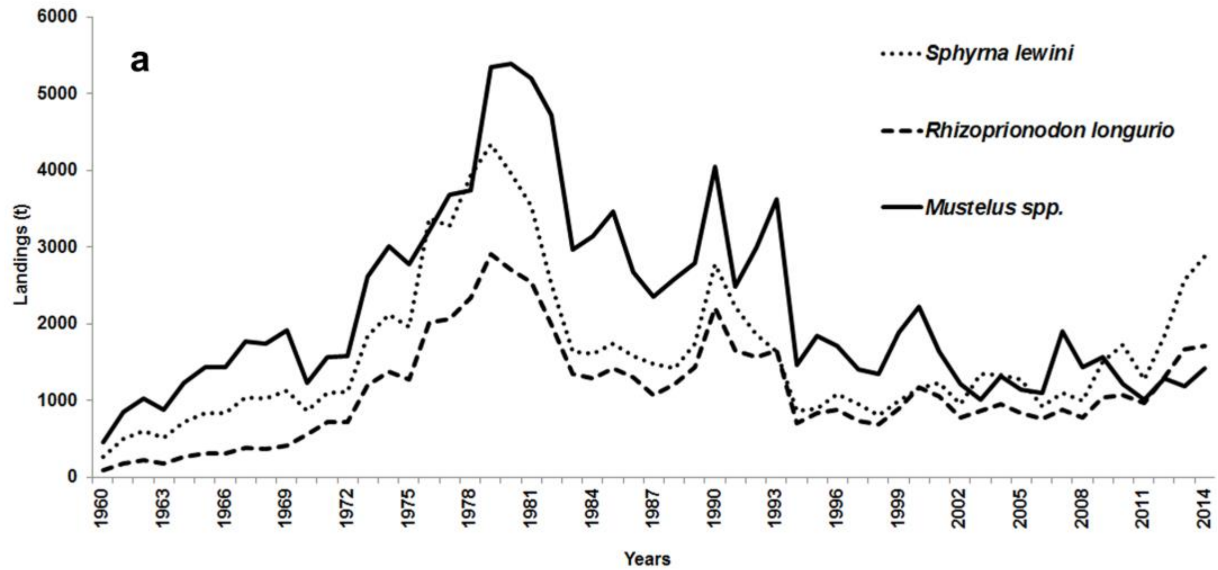
Table 4. List of shark species documented in the Gulf of California fisheries. Common and scientific names as per Page et al. (2013).

Species	**Common name**	**Family**
Heterodontus francisci	Horn shark	Heterodontidae
Heterodontus mexicanus	Mexican horn shark	Heterodontidae
Ginglymostoma cirratum	Nurse shark	Ginglymostomatidae
Alopias pelagicus	Pelagic thresher	Alopiidae
Alopias superciliosus	Bigeye thresher	Alopiidae
Alopias vulpinus	Common thresher shark	Alopiidae
Isurus oxyrinchus	Shortfin mako	Lamnidae
Cephaloscyllium ventriosum	Swell shark	Scyliorhinidae
Galeorhinus galeus	Tope	Triakidae
Mustelus albipinnis	Whitemargin smoothhound	Triakidae
Mustelus californicus	Gray smoothhound	Triakidae
Mustelus henlei	Brown smoothhound	Triakidae
Mustelus lunulatus	Sicklefin smoothhound	Triakidae
Triakis semifasciata	Leopard shark	Triakidae
Carcharhinus altimus	Bignose shark	Carcharhinidae
Carcharhinus brachyurus	Narrowtooth shark	Carcharhinidae
Carcharhinus falciformis	Silky shark	Carcharhinidae
Carcharhinus galapagensis	Galapagos shark	Carcharhinidae
Carcharhinus leucas	Bull shark	Carcharhinidae
Carcharhinus limbatus	Blacktip shark	Carcharhinidae
Carcharhinus longimanus	Oceanic whitetip shark	Carcharhinidae
Carcharhinus obscurus	Dusky shark	Carcharhinidae
Carcharhinus porosus	Smalltail shark	Carcharhinidae
Galeocerdo cuvier	Tiger shark	Carcharhinidae
Nasolamia velox	Whitenose shark	Carcharhinidae
Negaprion brevirostris	Lemon shark	Carcharhinidae
Prionace glauca	Blue shark	Carcharhinidae
Rhizoprionodon longurio	Pacific sharpnose shark	Carcharhinidae
Sphyrna corona	Scalloped bonnethead	Sphyrnidae
Sphyrna lewini	Scalloped hammerhead	Sphyrnidae
Sphyrna media	Scoophead	Sphyrnidae
Sphyrna mokarran	Great hammerhead	Sphyrnidae
Sphyrna tiburo	Bonnethead	Sphyrnidae
Sphyrna zygaena	Smooth hammerhead	Sphyrnidae
Hexanchus griseus	Bluntnose sixgill shark	Hexanchidae
Notorynchus cepedianus	Broadnose sevengill shark	Hexanchidae
Echinorhinus cookei	Prickly shark	Echinorhinidae
Squatina californica	Pacific angel shark	Squatinidae

2.3.3 Species-specific landings, 1960-2014

We estimated landings of 32 taxa: 30 species and the groups *Mustelus* spp. and *Sphyrna* spp. These estimates indicate several species with high average yearly landings, including *Mustelus* spp. (2,189 t), *S. lewini* (1,618 t) and *R. longurio* (1,128 t) (Figure 3a). Other species with considerable estimated landings were *C. falciformis, S. zygaena, C. limbatus* (Figure 3b), and *Squatina californica* (Figure 4a). For these taxa*,* the highest landings were seen in the late 1970s and early 1980s, followed by a decline from 1983 to 1994, and an increase after 2007.

Potential declines in landings for 16 (50%) shark species were observed (Figure 4). Landings of *C. leucas, N. velox* (Figure 4a), *Sphyrna* spp. (Figure 4b), *N. brevirostris* (Figure 4c) and *C. altimus* (Figure 4e) have decreased since the 1970s. Landings of *H. mexicanus, C. porosus* (Figure 4c)*, Carcharhinus obscurus, G. cuvier, C. galapagensis* (Figure 4d)*, Triakis semifasciata, H. francisci, C. ventriosum* (Figure 4e)*,* and *C. brachyurus* (Figure 4f) have decreased since the early 1980s, while landings of *C. longimanus* and *A. superciliosus* have decreased since 1994 (Figure 4f). In contrast, an increase in landings since the 1990's was observed for *P. glauca, Alopias pelagicus,* and *I. oxyrinchus* (Figure 4b).



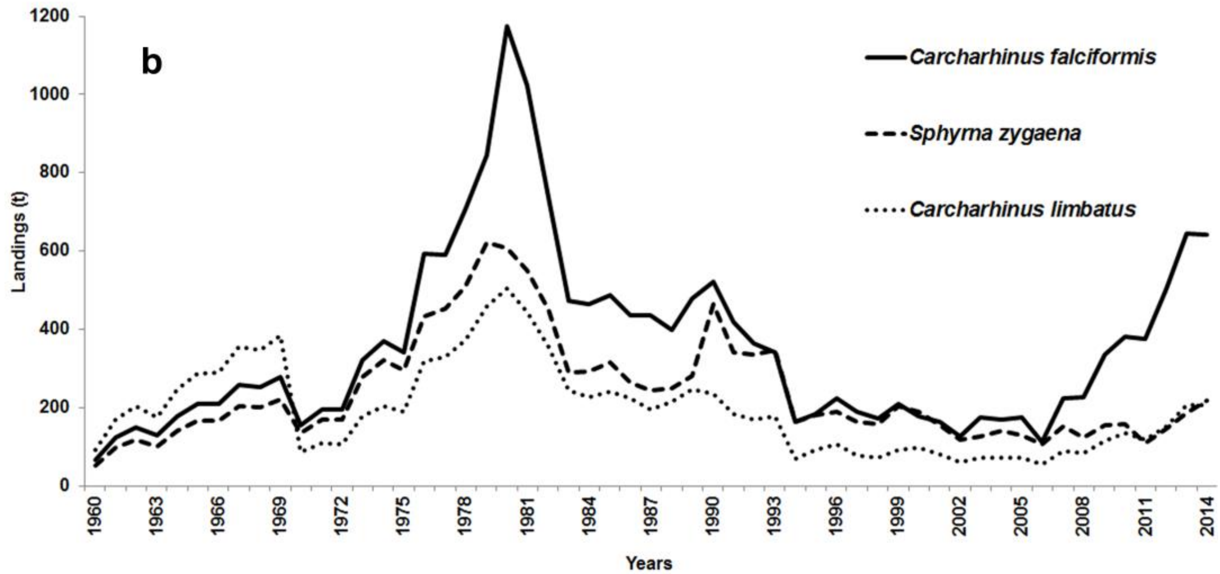


Figure 3. Reconstructed GC shark fishery landings for species with > 1,000 t: a) *Sphyrna lewini, Rhizoprionodon longurio* and *Mustelus* spp., and b) *Carcharhinus falciformis, Sphyrna zygaena* and *Carcharhinus limbatus.*

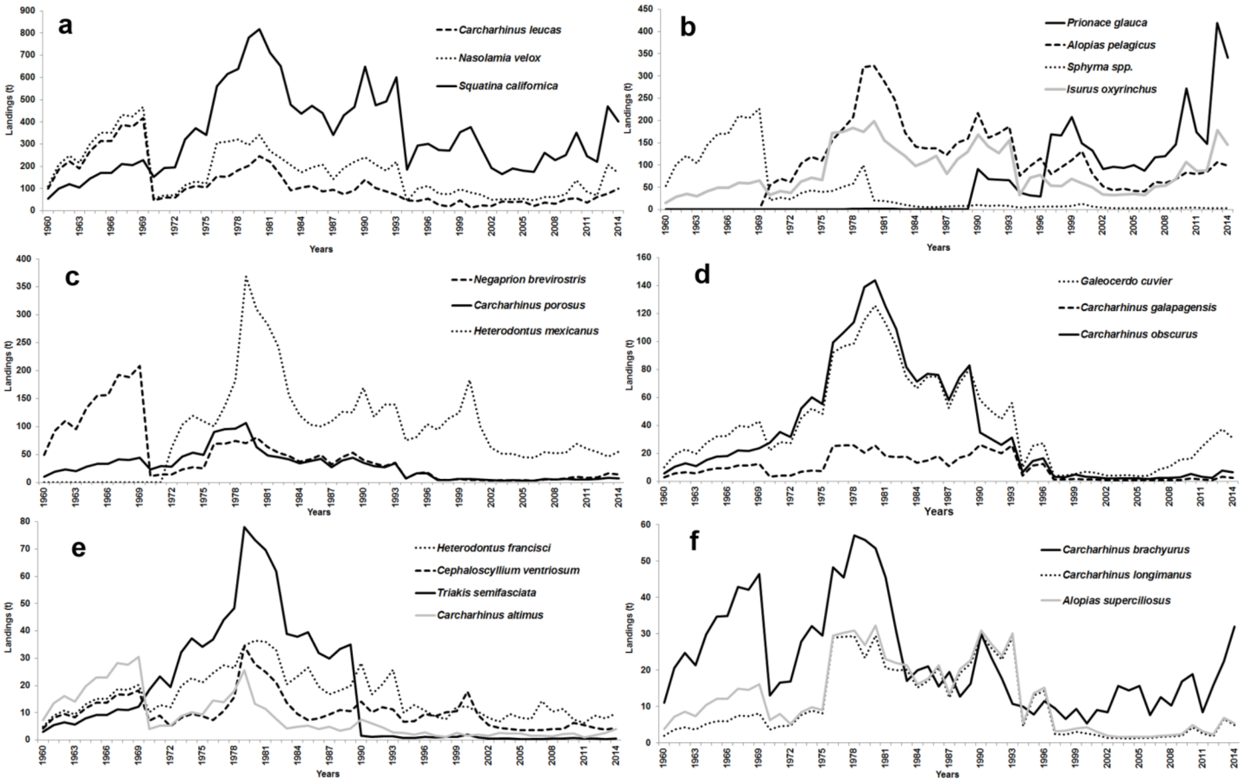


Figure 4. Reconstructed GC shark fishery landings for species with < 1,000 t: a) *Carcharhinus leucas, Nasolamia velox* and *Squatina californica*; b) *Prionace glauca, Alopias pelagicus, Sphyrna* spp., and *Isurus oxyrinchus;* c) *Negaprion brevirostris, Carcharhinus porosus* and *Heterodontus mexicanus*; d) *Galeocerdo cuvier, Carcharhinus galapagensis* and *Carcharhinus obscurus*; e) *Heterodontus francisci, Cephaloscyllium ventriosum, Triakis semifasciata,* and *Carcharhinus altimus*; and f) *Carcharhinus brachyurus, Carcharhinus longimanus,* and *Alopias superciliosus*.

2.3.4 Uncertainty

Uncertainty estimates for the reconstructed total landings (Figure 2) had wider confidence intervals for the period 1970-1976 (90%), followed by the periods 1939-1950 (50%), 1961-1969 (50%), 1951-1960 (30%), 1983-1991 (30%), 1977-1982 (20%) and 1992-2014 (20%). For the time period (1992 to 2014) in which only artisanal fishery uncertainty was assessed, the confidence interval was 20%. For the middle-sized vessel fishery, uncertainty confidence intervals were larger during the period 1988-2005 as compared to 2006-2014 (Figure 2).

2.4. Discussions

2.4.1 Potential impacts of markets and national fishery management policies on the shark landings in the Gulf of California

Our reconstruction of total shark landings suggests that landings have fluctuated between 1939 and 2014, and showed two notable increase and three notable declines. In recent years landings have been more stable. These fluctuations may be related to actual shark population trends, as well as environmental factors that influence both local shark abundance and the capacity of the fleet to access fishing grounds (Caddy and Gulland, 1983; Grande-Vida, 2006). Additionally, long-term landings fluctuations might also result from shifts in market forces and fishery management policies (Espinoza-Tenorio et al., 2011).

In Mexico, fishery policies have been characterized by constantly changing management objectives. In the case of GC shark fisheries, we suggest that the observed fluctuations of the reconstructed landings may be associated with historical changes in markets and management policies described in the literature (Ferreira, 1958; Hernández-Carvallo, 1971; Alcalá, 2003; Hernández and Kempton, 2003; Castillo-Géniz et al., 1998; Espinoza-Tenorio et al., 2011; Cisneros-Montemayor et al., 2013;). In the following discussion, we divided the trends of the shark fishing landings in the GC into five periods: 1) Rise and fall of the shark liver market (1939-1953), 2) Recovery and enhancement of the shark fisheries (1954-1970), 3) Fish as primary source of food and employment (1971-1980), 4) Neo-liberal reforms and their effects (1983-1994), and 5) Encouragement of sustainable development (1995-2000's) (Cisneros-Montemayor et al., 2013; Espinoza-Tenorio et al., 2011; Hernández-Carvallo, 1971).

2.4.1.1 Rise and fall of the shark liver market (1939-1953)

In 1888, the first exportation of shark fins from La Paz, BCS, to China was documented (Hernández-Carvallo, 1971); however, it was not until 1939 that shark liver export (from Guaymas, SON, to Los Angeles, CA) was first documented. During the 1940s, the high demand for vitamin A, extracted from shark livers, boosted GC shark landings (Hernández-Carvallo, 1971; Castillo-Géniz et al., 1998). The estimated landings in this study were higher than official records from 1940s reported by Castillo et al.

(2008) and Hernández-Carvallo (1971). These authors may have misinterpreted the reported landings as round weight. However, only the liver was used, and the rest of the meat was discarded (Berdegue, 1956). Shark landings peaked in 1942, and by 1943 several shark liver processing plants were built at Guaymas, SON, Mazatlán, SIN, and San Blas, NAY (Ferreira, 1958; Castillo-Géniz et al., 2008). Shark liver prices decreased from 1947 to 1950 (Ferreira, 1958), and landings subsequently decreased in 1951-1953 to less than 1% of the 1942 level.

2.4.1.2 Recovery and enhancement of the shark fisheries (1954-1970)

Due to increased demand for shark meat (dried, salt-dried, and fresh), GC shark landings once again increased after 1954 (Ferreira, 1958; Hernández-Carvallo, 1971). From the 1950s through the 1970s, Mexican fishery policies were intended to increase production, including shark products. Economic growth in Mexico allowed the government to enhance the fisheries sector by augmenting the national fleet, financing coastal industries, limiting foreign fisheries, and by developing government programs that increased the population and labour force in coastal communities (Alcalá, 2003; Espinoza-Tenorio et al., 2011). By the end of the 1960s, shark landings in the GC had increased to 4,000 t, with most product transported to Mexico City (Alcalá, 2003).

2.4.1.3 Fish as primary source of food and employment (1971-1980)

During the 1970s, Mexican government policies focused on promoting fisheries development and increasing landings to achieve greater economic growth (Hernández and Kempton, 2003; Espinoza-Tenorio et al., 2011). Policies during this period included technological improvement, increasing the size of the artisanal fleet, fishery loans granted by the National Bank for Fishing (BANPESCA), and a new Fisheries Law (Soberanes, 1994; Alcalá, 2003). The result was an exponential growth of GC shark landings, peaking in 1979 and 1980 at close to 18,000 t.

2.4.1.4 Economic crises, neo-liberal reforms and their effects (1981-1994)

The marked decline of estimated landings during 1981-1982 is likely related to a country-wide economic crisis in 1982. This caused the bankruptcy of the BANPESCA bank (which had provided financial support for fisheries) and the application of neoliberal reforms that withdrew federal government support for fisheries (Alcalá, 2003; Espinoza-Tenorio et al., 2011). The number of artisanal fishers increased during the 1980s and early 1990s, explaining the increase of shark landings during 1988 to 1992. This had the effect of hampering regulatory enforcement and the monitoring of fishing activities, potentially leading to resource overexploitation (Hernández and Kempton, 2003). Additionally, the economic crisis affected the reinvestment capacity of the fishing sector, resulting in the increased use of obsolete vessels and fishing gear (Alcalá, 2003; Hernandez-Kempton, 2003; Espinoza-Tenorio et al., 2011). To control fishing effort until the status of the exploited species was investigated, a suspension of new shark-fishing permits was enacted in 1993 (Castillo-Géniz *et al., 1998).* Further declines of TSL-GC during 1993 and 1994 resulted from a second countrywide economic crisis (Espinoza-Tenorio et al., 2011).

2.4.1.5 Encouragement of sustainable development (1995-2000's)

After 1995, Mexican fishery management policies were updated to encourage sustainability, including increased public participation, new scientific inputs and reduced fishing effort (Espinoza-Tenorio et al., 2011). These changes form the basis for the development of new fishery-specific Official Standard Regulations, or 'NOMs' (Hernández and Kempton, 2003). In 2007, the NOM-029-PESCA-2006 was established, and included specific regulations for the shark and ray fisheries throughout Mexico (Sosa-Nishizaki, 2008). This included the integration of a national information system of biological and fishery data, fishery effort limits, area and seasonal closures, prohibition of shark finning, a ban on drift gill-net fishing by medium-size vessels, and fishing bans for several protected species (DOF, 2007). Recently, a temporary ban on fishing for sharks and rays in the Mexican Pacific, including the GC, was established during summer months (from 1 May to 31 July). The rationale for this ban is based upon studies of the abundance of gravid females during this period, thereby giving priority to increased parturition rates of rays and sharks and positive recruitment to the populations that support the fisheries (DOF, 2012). The results of this measure will only be quantifiable in the long term, but may account for the relatively stable trend of the last reconstructed landings period.

2.4.2 Uncertainty

Reconstruction of fishery landings provides an opportunity to explore alternative sources of data and to provide explanations for the observed trends (Thurstan et al., 2016). However, using a reconstruction method such as ours is associated with data uncertainty related to the use of non-standardized data sources (Zeller et al., 2007). Nevertheless, the information used in the present study was the best available. Our evaluation of uncertainty was based on the quality of the time series and the assumptions and methods used in each period and for each fishing fleet. We did not try to adjust our landing series to include unreported landings, because estimations of the ratio of unreported to reported landings for each of the period we analysed were unavailable. However, we were aware that the ratio has decreased over time from over 4:1 in 1950 to 0.45:1 in 2010 (Cisneros-Montemayor et al., 2013), and this was considered during our uncertainty estimations.

During the first period (1939-1950) of the artisanal fishery, the conversion factor for liver weight to rounded weight was the main source of uncertainty (i.e., larger confidence intervals), since it was not specific to the shark species found in the GC (FAO, 2000). During the 1951 to 1960 period, smaller estimated confidence intervals were due to the use of historical literature and official statistics from the GC (Secretaría de Marina, 1940-1969 Berdegue, 1956; Alcalá-Moya, 1999). For time periods after 1960, we obtained shark landings records from official yearbooks (SEMARNAP, 2000), but the size of the estimated confidence intervals was primarily related to the availability of fishing records from local FOs. During the last analysed period (1992-2014), confidence intervals were tighter due to the detailed descriptions of artisanal fisheries in several studies conducted 1997-1999 (Villavicencio-Garayzar, 2000; Bizzarro et al., 2009a, b, c; Smith et al., 2009).

For the middle-sized vessel shark fishery, uncertainty confidence intervals for the estimated shark landings reflect the assumption that all shark landings recorded at Mazatlán, SIN, came only from this fishery operating in the GC. However, a proportion of the fleet’s fishing activity likely occurred in oceanic waters off the tip of the Baja California peninsula and at the Revillajijedo islands (Corro-Espinosa et al., 2014). In addition, past shark landings have been reported for middle-sized vessels targeting shrimp and teleost fishes that once operated in the north part of the GC (Corro-Espinosa et al., 2014; Godínez-Padilla and Castillo-Géniz, 2016).

2.4.3 Species composition in the artisanal fishery in the Gulf of California, 1960-2014

Our species compositions estimations are based on bold assumptions and fragmented data due to catch composition data gaps for the GC artisanal shark fishery. The uncertainty intervals for our estimates were lowest for the years with detailed quantitative data (e.g., 1995-2001 and 2007-2010). For example, for the 1970s, the species descriptions were general, with very limited fishery information. And for the last years of the time series (2010s), there were few fisheries studies in the GC region, and hence, scarce species composition data.

However, our approach is based on an exhaustive search for, and integration of, historical data (qualitative and quantitative) to prevent relevant information from being lost. Such estimates elucidate important insights into historic landings trends for many species, particularly for data-poor fisheries (McClenachan et al., 2012). Moreover, the species composition of landings, considered by state, allows some insight into geographic distribution. For example, oceanic species such as *P. glauca* were more frequently recorded in the landings of BCS and NAY (southern GC) and less commonly in BC and SON. Many demersal species, such as *M. henlei*, were more commonly landed in BC and SON (Pérez-Jiménez et al., 2005; Bizzarro et al., 2009a, b, c; Smith et al., 2009; Mondragón Sánchez, 2011).

Several shark taxa, including *Mustelus* spp., *S. lewini, R. longurio*, *C. falciformis, S. zygaena, S. californica,* and *C. limbatus,* have been important for the GC artisanal shark fishery since at least the 1960s (Kato and Hernández-Carvallo, 1967; Hernández-Carvallo, 1971). This is consistent with our elevated estimated landings for these taxa. In addition, *S. lewini, S. zygaena*, *R. longurio*, *Mustelus* spp., and *C. limbatus* can be traced back to the late 1930s as targets of the artisanal fishery. Initially, *S. lewini*, *S. zygaena*, and *C. limbatus* were targeted for their liver and *R. longurio*, *M. lunulatus,* and *M. californicus* for their meat (Berdegue, 1956; Hernández-Carvallo, 1971). Thus, these taxa have supported fishing pressure for more than seven decades.

Mustelus spp., *S. lewini*, *R. longurio and C. limbatus* landings increased slightly during the last three years of the time series. However, it is unknown whether this is related to vulnerability to changing fishing gear or to variations in their overall biomass in the GC ecosystem. For example, *Mustelus* spp. is a group of four species (*M. californicus, M. henlei, M. lunulatus*, and *M. albipinnis*), each with specific biological characteristics that make them respond differently to fishing pressures (Smith et al., 1998), and therefore should ideally be analysed individually.

Some GC shark species (e.g., *M. californicus* and *R. longurio*) are known to be highly productive, and therefore less vulnerable to directed fisheries (Smith et al., 1998; Furlong-Estrada et al., 2014). Conversely, *S. lewini* is a low productivity species (Furlong-Estrada et al., 2014), and was recently was classified as 'Endangered' by the International Union for Conservation of Nature and Natural Resources (IUCN) and included in Appendix II of CITES to control the international trade (Baum et al., 2007; CITES, 2013). These findings illustrate that a comprehensive revision of the biological parameters of all species and their current population status and exploitation level should be done to address sustainable management in GC fisheries.

Several species such as *C. falciformis, S. zygaena,* and *S. californica* have been landed in the GC since the 1960s (Kato and Hernández-Carvallo, 1967; Hernández-Carvallo, 1971), but landings of these species increased in the late 1970s and the early 1980s (Applegate et al., 1979), and are still substantial in the GC artisanal fishery (Galván-Magaña et al., 1989; Salomón-Aguilar et al., 2009; Torres-Herrera and Tovar-Avila, 2014). Future studies should focus on determining the populations status of such species to evaluate the capacity of these species to support fishing pressure from the GC artisanal shark fishery.

Our reconstructed landings showed declines for several species. *Carcharhinus leucas* was intensively fished and economically important in Mexican fisheries in the 1960s, 1970s and 1980s (Hernández-Carvallo, 1971; Applegate et al., 1979, 1993). *Nasolamia velox* was particularly important in the southern GC landings in the 1960s (Kato, 1965; Ramírez-Hernandez and Arvizu Martinez, 1965; Hernández-Carvallo, 1971). *Negaprion brevirostris,* and several species of hammerheads (e.g., *S. mokarran, S. tiburo, S. media, S. zygaena,* and *S. lewini*), were prized catch during the 1940s for their high market value livers (Berdegue, 1956; Hernández-Carvallo, 1971). *Carcharhinus altimus* was also exploited for its liver, but less frequently than the species listed above (Hernández-Carvallo, 1971; Applegate et al., 1979).

Considerable decreases in the estimated landings were observed for these taxa. However, for *C. altimus* the estimated landings do not exceed the 30 mt in all the time series. Based on interviews with elder GC fishers, *C. leucas*, *Sphyrna* spp. *G. cuvier*, and *C. limbatus* were larger and more abundant in the past (Sáenz-Arroyo et al., 2005), and the proportions in the landings of GC artisanal fishery of *C. leucas, N. velox,* and *C. altimus* have been low since the late 1990s (Márquez-Farías, 2000; Villavicencio-Garáyzar, 2000; Pérez-Jiménez et al., 2005; Bizzarro et al., 2009a, b, c; Mondragón Sánchez, 2011; Smith et al., 2009). *Sphyrna tiburo, S. media, S. corona,* and *S. mokarran* have not been observed in the landings since the 1990s, and in recent years were described as "likely extirpated" from the GC (Pérez-Jiménez, 2014).

The species *C. obscurus, G. cuvier, C. porosus, T. semifasciata,* and *C. brachyurus* were abundant in landings in the 1970s and 1980s (Applegate et al., 1979; Van der Heiden, 1985; Castillo-Géniz et al., 1996; Sáenz-Arroyo et al., 2005), but less common in recent landings (Márquez-Farías, 2000; Guerrero Maldonado, 2002; Bizzarro et al., 2009a). *Carcharhinus obscurus, G. cuvier, C. porosus, T. semifasciata,* and *C. brachyurus* had low abundance in the base proportions used for the species composition estimations (Bizzarro et al., 2009a, c; Smith et al., 2009) which could explain the low estimated landings over the entire time series. The estimated landings of *H. mexicanus, C. galapagensis, H. francisci, C. ventriosum, C. longimanus,* and *A. supercilious* also decreased, although these species were never an important component of the historic (and recent) fishery (Berdegue, 1956; Hernández-Carvallo, 1971; Applegate et al., 1979; Castillo-Géniz, 1992; Márquez-Farías, 2000; Guerrero Maldonado, 2002; Bizzarro et al., 2007). Future efforts to monitor biomass trends and fishing effort for these species are required to understand their status and exploitation levels.

From the 1950s to early 1990s, *P. glauca* was described as abundant in the GC, but with low relevance for the fishery (Berdegue, 1956; Kato and Hernández-Carvallo, 1967; Applegate et al., 1979; Castillo-Géniz, 1992). However, estimated landings of *P. glauca* have increased considerably since the 1990s, especially in the southern GC (Guerrero Maldonado, 2002; Bizzarro et al., 2009b). The estimated landings of other pelagic sharks such as *I. oxyrinchus* and *A. pelagicus* have also increased, but more gradually. Both species are commonly caught in the fishery since the late 1980s (Applegate et al., 1979; Castillo-Géniz et al., 1996; Arenas and Díaz de León, 2000).

Finally, the species with the lowest estimated landings (*E. cookei, G. cirratum, A. vulpinus, H. griseus, G. galeus*, and *N. cepedianus*) were described as uncommon in the GC artisanal fishery landings in the late 1990s (Bizzarro et al., 2009a, b). Species like *E. cookei, H. griseus, G. galeus*, and *N. cepedianus,* were historically rare in the GC landings (Applegate et al., 1979; Villavicencio-Garayzar, 1996), consistent with our estimates. Other species, like *G. cirratum* and *A. vulpinus,* were common in the GC artisanal fishery landings through the 1980s (Berdegue, 1956; Applegate et al., 1979; Applegate et al., 1993; Rodríguez De La Cruz et al., 1994) but less common in recent years (Márquez-Farías, 2000; Bizzarro et al., 2007) and should be monitored.

2.4.4 Management considerations

The slow growth and low reproductive rates of most shark species, compared to teleost fishes, makes them vulnerable to exploitation (Drymon and Scyphers, 2017). Quantitative assessment of exploited shark populations requires accurate fishery effort and landings records (Clarke et al., 2006). The lack of such records, as well as the heterogeneity of the shark fisheries in Mexico, makes management implementation and enforcement extremely difficult in the GC *(*Applegate et al., 1993; Pérez-Jiménez and Mendez-Loeza, 2015).

In the GC, many fishing camps are located in remote areas with rugged volcanic terrain, especially in BC and BCS (Bizzarro et al., 2009b; Smith et al., 2009). These conditions make it difficult to monitor the artisanal fishery activities (location of the active camps, fishery regions, catch composition of the landings, and fishing season and effort). In the state of NAY, the fishing camps are more accessible, with a greater infrastructure than in BC and BCS, but in some sites (e.g., La Cruz de Huanacaxtle) the shark fisheries operate seasonally, and during the spring-summer period fisherman move to northern regions in the GC (SON, SIN or BCS) to fish for sharks (Furlong-Estrada and Barragan-Cuencas, 1997). In the past, an influx of shark fishers in the GC occurred mostly in the states of BC and BCS, where an itinerant population travelled seasonally from Chiapas (Bizzarro et al., 2007), causing unknown variability in the number of vessels fishing in the GC.

Current Mexican shark fishery management measures consider sharks as a group, except those of species of special conservation concern (DOF, 2007; 2012). Our results suggest that there could be great differences in species landings between the artisanal and middle-sized vessel fisheries. For example, the case of *P. glauca* in the current study highlights the necessity of species-specific management. While *P. glauca* is considered to be of ‘medium’ abundance in GC artisanal fishery landings, it is the one of the highest abundance species in the middle-sized vessel landings at Mazatlan, SIN (Corro-Espinosa et al., 2014), and this affects the general trend of total GC shark landings. While artisanal landings of other shark species had declined, total GC shark landings increased since 2002 (Figure 2), mostly due to an increase of *P*. *glauca* landings from medium size vessels. Most of these sharks were captured in offshore waters just outside of the GC (Corro-Espinosa, 2016). Analyses of shark landings by species could help to avoid future misinterpretations of GC shark fishery data.

The implementation of species-specific management strategies can be achieved by the collection of the biological and fishery data, with a special emphasis on species that have supported intense fishing effort for many years. Continuous monitoring of landings is required to determine seasonality of the fishery, more accurate species identification and fishing effort data, and to determine susceptibility of various shark species to the fishery (Barker and Schluessel, 2005), as well as to evaluate the effectiveness of management measures. In addition, it is important to investigate life history patterns for each species (Smith et al., 1998). Attention should be paid to the identification of shark mating and nursery areas to determine their role in recruitment, since it has been suggested that the presence of these areas in the GC is important for several shark species such as *S. lewini, R. longurio, S. californica, C. falciformis, C. limbatus, S. zygaena, M. henlei* and *M. Lunulatus* (Heupel and Simpfendorfer, 2007; Salomon-Aguilar et al., 2009). Finally, a key element in successful fishery management is the active participation and collaboration of stakeholders, that will increase the users' commitment and responsibility to the new regulations (Hernández and Kempton, 2003; Simpfendorfer et al., 2011).

2.5 Conclusions

This study provides insight into the historical trends of the shark landings of the GC artisanal fishery for the period 1939-2014, middle-size vessel fishery landings for the 1988 to 2014, and species composition of these landings for the 1960 to 2014 period. Thirty eight shark species were identified in the GC artisanal fishery. *Sphyrna lewini*, *R. longurio, S. californica, C. falciformis, Sphyrna zygaena,* and *C. limbatus* and *Mustelus* spp. have supported intense fishing pressure for more than five decades. Conversely, taxa with marked declines in landings (e.g., *C. leucas, N. velox, N. brevirostris, Sphyrna* spp., *C. altimus, C. obscurus, G. cuvier, C. porosus, T. semifasciata,* and *C. brachyurus*) should be the focus of future research to estimate their population abundance and growth. Our findings present a baseline for understanding changes in species composition and abundance through time in the GC. Although the estimated landings presented herein cannot be considered as absolute values, they can be used as reference points for landings trends. These estimated landings provide the first view of the fishing pressure that several species have been subject to throughout the years and identifies species on which to focus future research efforts to determine population status in the GC.

Chapter 3. Ecological risk assessment of sharks caught in the Gulf of California artisanal fisheries: considerations for management and future research

3.1 Introduction

In many shark fisheries in the world the evaluation of the populations through conventional methods – e.g. formal stock assessments- cannot be achieved due to the lack of historical catch and effort records and information on the life history for several species that have impeded the estimation of abundance indices (Carruthers et al., 2014). In consequence, these fisheries are poorly regulated and the knowledge of the status of the populations is unknown (Fowler et al. 2005; Bonfil, 1994). This is the case of many small-scale fisheries–also called artisanal fisheries- that usually are multi-specific (Pilling et al., 2008).

Mexico has an important shark fishery across the country, with more than 28,193 tons landed in the year of 2014–the 13th place among all fisheries in the country-and around 42 percent of these catches came from the artisanal fishery in the Gulf of California (SAGARPA, 2015; Saldaña-Ruiz et al. submitted manuscript, 2016a). Despite its importance, to determinate the fishing effort intensity–and thus infer the status of the populations- is a difficult task due to the following reasons: the complexity of the fishery, due the multispecies caught; for most species, available biological data are limited; and official catch records by species are absent (Bonfil, 1994; Bizzarro et al., 2007). Therefore, it is not possible to develop a well-planned management plan to ensure the sustainability of the fishery.

In recent years, methods to evaluate the fish populations under a fishery regime with data-poor situations have developed (Cortés et al., 2015; Patrick et al. 2010). One of these methods is the Productivity and Susceptibility Analysis (PSA). The PSA is a rapid risk assessment to determine the probable vulnerability (risk) of the species to become overfished. It evaluates the capacity at which species populations can recover after potential fishery depletion (Productivity), and the potential impact of the fishery on the species (Susceptibility) (Hobday et al., 2007; Cortés et al., 2010).

The PSA is a flexible method that can be easily adapted to any fishery and has been widely used for many fisheries in the Atlantic, in the Indian Ocean, in Australia, in the USA and also in Mexico (Arrizabalaga et al., 2011; Cortés et al., 2009; Kiszka, 2012; Hobday, et al., 2011; 2007; Stobutzki et al., 2002; Braccini et al., 2006; Furlong-Estrada et al., 2014; Pérez-Jiménez, 2014a; Garcés García, 2012). This methodology has also been recommended by the Australian Fisheries Management Authority (Hobday et al., 2007), the

International Commission for the Conservation of Atlantic Tunas (ICCAT) Ecosystems Working Group (ICCAT 2008) and the United States National Oceanographic and Atmospheric Administration (NOAA) (Patrick et al., 2009).

The purpose of this study was to identify the shark species with high relative vulnerability to the artisanal fishery in the Gulf of California using a PSA approach modified by Patrick et al., (2009). The vulnerability (or risk to overexploitation) was determined for 38 shark species and the results were compared with historical catch estimations by species made by Saldaña-Ruiz et al. (submitted manuscript, 2016a) to identify those needing more attention in terms of more robust analysis.

3.2. Materials and methods

Vulnerability to overfishing was evaluated in 38 species of sharks of the artisanal fisheries in the Gulf of California (GC) (Pérez Jiménez et al., 2005; Smith et al., 2009; Bizzarro et al., 2009a,b,c; Villavicencio-Garáyzar, 2000; Mondragón Sánchez, 2011) (species are listed Table 5). Biological, ecological and fishery data were collected from the literature for each species. Also, the status for each species in the Convention on International Trade in Endangered Species of Wild Fauna and Flora(CITES) and in the International Union for Conservation of Nature and Natural Resources red list (IUCN) was obtained. All collected information was used to create an extensive database organized by species and geographical origin and sources of the data.

3.2.1. Productivity, susceptibility and vulnerability

The vulnerability of the shark species was obtained by a PSA with modifications made by Patrick et al. (2009). This analysis estimates the relative vulnerability of the species (teleost and shark species) as a function of its productivity and susceptibility. The productivity is related with the life history of the species, as a measure of its recovery capacity after potential reduction by fishing, while the susceptibility is the potential for the species to be impacted by the fishery (Hobday et al., 2007). The productivity and susceptibility were determined by scoring a set of attributes from 1 to 3 (low, medium and high). But, previous to the productivity and susceptibility scoring process, each of the attributes was assigned a weighting value from 0 to 4, related with its perceived contribution to the overall productivity or susceptibility score, where a weighting of zero means that the attribute is removed from the analysis due to its lower contribution to the productivity or susceptibility. The attribute sets for productivity and susceptibility and the scoring process criteria are listed in Table 6 and 7 (Patrick et al., 2009).

Table 5. Shark species recorded in the catches of the artisanal fishery in the Gulf of California and their IUCN and CITES status.

Species	**Code**	**Common name**	**Status (IUCN/CITES)**
Sphyrna lewini	1	Scalloped hammerhead	Endangered/ II*
Mustelus henlei	2	Brown Smooth-hound	Least Concern
Rhizoprionodon longurio	3	Pacific Sharpnose Shark	Data Deficient
Mustelus californicus	4	Gray Smooth-hound	Least Concern
Mustelus lunulatus	5	Sicklefin Smooth-hound	Least Concern
Mustelus albipinnis	6	White-margin Fin Hound Shark	Data Deficient
Carcharhinus falciformis	7	Silky Shark	Near Threatened
Squatina californica	8	Pacific Angel Shark	Near Threatened
Prionace glauca	9	Blue shark	Near Threatened
Sphyrna zygaena	10	Smooth Hammerhead	Vulnerable/ II
Carcharhinus limbatus	11	Blacktip Shark	Near Threatened
Nasolamia velox	12	Whitenose Shark	Data Deficient
Heterodontus mexicanus	13	Mexican Hornshark	Data Deficient
Isurus oxyrinchus	14	Shortfin Mako	Vulnerable
Alopias pelagicus	15	Pelagic Thresher, Whiptail Shark	Vulnerable
Carcharhinus leucas	16	Bull Shark-Sand tiger	Near Threatened
Galeocerdo cuvier	17	Tiger Shark	Near Threatened
Ginglymostoma cirratum	18	Nurse Shark	Data Deficient
Carcharhinus brachyurus	19	Copper Shark	Near Threatened
Negaprion brevirostris	20	Lemon Shark	Near Threatened
Chephaloscyllium ventriosum	21	Swell Shark	Least Concern
Carcharhinus obscurus	22	Dusky Shark	Vulnerable
Alopias superciliosus	23	Bigeye Thresher hark	Vulnerable
Carcharhinus longimanus	24	Oceanic Whitetip Shark	Vulnerable/ II
Carcharhinus porosus	25	Smalltail Shark	Data Deficient
Carcharhinus altimus	26	Bignose Shark	Data Deficient

Carcharhinus galapagensis	27	Galapagos Shark	Near Threatened
Echinorhinus cookei	28	Spinous Shark	Near Threatened
Triakis semifasciata	29	Leopard Shark	Least Concern
Alopias vulpinus	30	Thresher Shark	Vulnerable
Heterodontus francisci	31	Bullhead Shark	Data Deficient
Hexanchus griseus	32	Bluntnose Sixgill Shark	Near Threatened
Notorynchus cepedianus	33	Broadnose Sevengill Shark	Data Deficient
Galeorhinus galeus	34	School-Tope shark	Vulnerable
Sphyrna corona	35	scalloped bonnethead	Near Threatened
Sphyrna media	36	Scoophead	Data Deficient
Sphyrna mokarran	37	Great hammerhead	Endangered/ II
Sphyrna tiburo	38	Bonnethead	Least Concern

*Appendix II of CITES regulates their commercial trade because the species is heavily exploited, has low productivity or an extreme historical decrease in population (CITES, 2013).

Table 6. Productivity attributes and scores used to determine the vulnerability of the shark species to the artisanal fishery in the Gulf of California.

	Criteria to score		
Productivity Attributes	**High (3)**	**Moderate (2)**	**Low (1)**
Intrinsic growth rate (r)	>0.5	0.5-0.16 (mid-pint 0.10)	<0.16
Maximum Age	< 10 years	10 - 30 years (mid-point 20)	> 30 years
Maximum Size	< 60 cm	60-150 cm (mid-point 105)	> 150 cm
von Bertalanffy Growth Coefficient (k)	> 0.25	0.15-0.25 (mid-point 0.20)	< 0.15
Estimated Natural Mortality	> 0.40	0.20-0.40 (mid-point 0.30)	< 0.20
Measured Fecundity	> 10e4	10e2-10e3	< 10e2
Breeding Strategy	0	between 1 and 3	≥4
Age at Maturity	< 2 years	2-4 years (mid-point 3.0)	> 4 years
Mean Trophic Level	<2.5	2.5-3.5 (mid-point 3)	>3.5

Table 7. Susceptibility attributes and scores used to determine the vulnerability of the shark species to the artisanal fishery in the Gulf of California.

	Criteria to score		
Susceptibility Attributes	**Low (1)**	**Moderate (2)**	**High (3)**
Management Strategy	Targeted stocks have catch limits and proactive accountability measures; Non-target stocks are closely monitored.	Targeted stocks have catch limits and reactive accountability measures	Targeted stocks do not have catch limits or accountability measures; Non-target stocks are not closely monitored.
Areal Overlap	< 25% of stock occurs in the area fished	Between 25% and 50% of the stock occurs in the area fished	> 50% of stock occurs in the area fished
Geographic Concentration	stock is distributed in > 50% of its total range	stock is distributed in 25% to 50% of its total range	stock is distributed in < 25% of its total range
Vertical Overlap	< 25% of stock occurs in the depths fished	Between 25% and 50% of the stock occurs in the depths fished	> 50% of stock occurs in the depths fished
Fishing rate relative to M	<0.5	0.5 - 1.0	>1
Biomass of Spawners (SSB) or other proxies	B is > 40% of B0 (or maximum observed from time series of biomass estimates)	B is between 25% and 40% of B0 (or maximum observed from time series of biomass estimates)	B is < 25% of B0 (or maximum observed from time series of biomass estimates)
Seasonal Migrations	Seasonal migrations decrease overlap with the fishery	Seasonal migrations do not substantially affect the overlap with the fishery	Seasonal migrations increase overlap with the fishery
Schooling/Aggregation and Other Behavioral Responses	Behavioral responses decrease the catchability of the gear	Behavioral responses do not substantially affect the catchability of the gear	Behavioral responses increase the catchability of the gear [i.e., hyperstability of CPUE with schooling behavior]
Morphology Affecting Capture	Species shows low selectivity to the fishing gear.	Species shows moderate selectivity to the fishing gear.	Species shows high selectivity to the fishing gear.
Survival After Capture and Release	Probability of survival > 67%	33% < probability of survival < 67%	Probability of survival < 33%
Desirability/Value of the Fishery	stock is not highly valued or desired by the fishery	stock is moderately valued or desired by the fishery	stock is highly valued or desired by the fishery
Fishery Impact to EFH or Habitat in General for Non-targets	Adverse effects absent, minimal or temporary	Adverse effects more than minimal or temporary but are mitigated	Adverse effects more than minimal or temporary and are not mitigated

The overall productivity and susceptibility were calculated as the weighted average of all scored attributes and then displayed in an x-y scatter plot–PSA plot. The score results of productivity and susceptibility were divided into three categories: low (1 to 1.67), medium (1.68 to 2.34) and high (2.35 to 3). Vulnerability for each species was calculated as

$$V = \sqrt{[(P - X_0)^2 + (S - Y_0)^2]} \tag{1}$$

Where vulnerability (V) is defined as the Euclidean distance from the origin of the PSA plot (X_0, Y_0) to the data point of productivity (P) and susceptibility (S) (Figure 5) (Patrick et al. 2009). The species with high V to overfishing are those with low P score and high S score, while the least vulnerable species are those with high P score and low S score (Stobutzki et al., 2001; Hobday et al., 2011; Patrick et al., 2010).

The PSA plot divided into three regions of equal V (risk) by two contour lines that are the limits between V categories of low (V < 0.94), moderate (0.94> V <1.88), and high (V ≥1.89). The reference points used to establish these V categories were the maximum (2.82) and the minimum (0) possible values of V (see Figure 5.) Additionally, the level of confidence of the data used to score the P and S was determined by scoring the quality of the data in a scale from 1 (the best data available) to 5 (no data) (Table 8). For display purposes, the data quality scores were categorized into: good (<2, green), medium (2 to 3.5, ellow) and poor data (> 3.5, red).

The weighting, attribute scoring process and data quality evaluation were analyzed in several workshops with academic and government sectors experienced in artisanal fisheries in the GC and ecological risk assessment analysis. The PSA scoring process and x-y scatter plots were made with the PSA software VERSION 1.4.0.0, developed in 2010 by NOAA.

Table 8. Criteria used to score data quality in the PSA analysis by species. Modified of Patrick et al., 2010.

Data quality score	Description
1	**Best data.** Information based on collected data for the stock in the Gulf of California.
2	**Adequate data.** Information based on limited coverage and corroboration and from species in other regions of the Pacific.
3	**Limited data.** Estimates with high variation and limited confidence. Species in other regions of the world
4	**Very limited data.** Information based on expert opinion or on general literature reviews from a wide range of species (similar taxa)
5	**No data**

3.2.2. Sensitivity analysis

One way to deal with the uncertainty of the limited species-specific data available for the shark species analyzed, was the consultation with experts. Additionally, we analyzed the sensitivity of the scoring process for the attributes most deficient in data. We formulated nine types of scoring combinations for the entire 38 shark species of the following susceptibility attributes: Fishing mortality rate, in relation to M (F) and Biomass of spawners (B) (Table 9). From these nine scoring combinations we obtained the 'best case' scenario–lowest susceptibility score–and the 'worst case' scenario–highest susceptibility score-to observe how the resulting vulnerability varies with each scenario and establish the relative importance of the input scores.

Table 9. The nine scoring combinations for the susceptibility attributes of fishing mortality rate (F) and biomass of spawners (B). The white cell represents the 'best case' scenario and the black cell the 'worst case' scenario.

		B scores		
		Low (1)	Moderate (2)	High (3)
F scores	Low (1)	**F_1-B_1**	**F_1-B_2**	**F_1-B_3**
	Moderate (2)	**F_2-B_1**	**F_2-B_2**	**F_2-B_3**
	High (3)	**F_3-B_1**	**F_3-B_2**	**F_3-B_3**

3.3 Results

3.3.1 Productivity, susceptibility and vulnerability

According to this analysis, most species of sharks (89%) had low productivity, the remaining species (10.5%) had moderate productivity; none of the species resulted with high productivity (Table 6). Among the species analyzed, *R. longurio, S. tiburo, Mustelus californicus* and *A. vulpinus* were the most productive; and species with the lowest productivity were *C. leucas, C. obscurus, G. galeus* and *S. mokarran* (Table 10).

Susceptibility results show that only one species, *M. californicus,* is highly susceptible to the fishing activities of the GC. The majority of the species (66%) are moderately susceptible and only 12 species (31%) have low susceptibility to the fishing activities (Table 10).

Table 10. Productivity, susceptibility, vulnerability values and their categories (low, moderate and high) of the 38 shark species in the artisanal fishery of the Gulf of California. Vulnerability rank (lower number indicates higher vulnerability) is also indicated.

Species	Species Code	Productivity	Category	Susceptibility	Category	Vulnerability	Vulnerability rank	Category
Carcharhinus leucas	16	1	Low	2.04	Moderate	2.25	1	High
Sphyrna lewini	1	1.15	Low	2.11	Moderate	2.15	2	High
Carcharhinus obscurus	22	1	Low	1.75	Moderate	2.14	3	High
Squatina californica	8	1.15	Low	2.07	Moderate	2.13	4	High
Triakis semifasciata	29	1.12	Low	2	Moderate	2.13	5	High
Ginglymostoma cirratum	18	1.15	Low	2.04	Moderate	2.12	6	High
Sphyrna mokarran	37	1	Low	1.71	Moderate	2.12	7	High
Carcharhinus brachyurus	19	1.12	Low	1.93	Moderate	2.1	8	High
Sphyrna zygaena	10	1.19	Low	1.96	Moderate	2.05	9	High
Galeorhinus galeus	34	1	Low	1.43	Low	2.05	10	High
Carcharhinus falciformis	7	1.19	Low	1.86	Moderate	2	11	High
Isurus oxyrinchus	14	1.08	Low	1.46	Low	1.98	12	High
Carcharhinus galapagensis	27	1.25	Low	1.93	Moderate	1.98	13	High
Negaprion brevirostris	20	1.16	Low	1.64	Low	1.95	14	High
Alopias pelagicus	15	1.17	Low	1.57	Low	1.91	15	High
Carcharhinus longimanus	24	1.25	Low	1.77	Moderate	1.91	16	High
Nasolamia velox	12	1.15	Low	1.39	Low	1.89	17	High
Notorynchus cepedianus	33	1.31	Low	1.79	Moderate	1.87	18	Moderate
Carcharhinus porosus	25	1.37	Low	1.88	Moderate	1.85	19	Moderate
Alopias superciliosus	23	1.19	Low	1.21	Low	1.82	20	Moderate
Mustelus californicus	4	1.88	Moderate	2.43	High	1.81	21	Moderate
Mustelus henlei	2	1.67	Low	2.21	Moderate	1.8	22	Moderate
Sphyrna media	36	1.35	Low	1.71	Moderate	1.8	23	Moderate
Galeocerdo cuvier	17	1.35	Low	1.68	Moderate	1.79	24	Moderate
Heterodontus francisci	31	1.42	Low	1.86	Moderate	1.79	25	Moderate
Mustelus albipinnis	6	1.35	Low	1.43	Low	1.71	26	Moderate

Carcharhinus altimus	26	1.42	Low	1.64	Low	1.7	27	Moderate
Heterodontus mexicanus	13	1.58	Low	1.89	Moderate	1.68	28	Moderate
Mustelus lunulatus	5	1.6	Low	1.79	Moderate	1.61	29	Moderate
Carcharhinus limbatus	11	1.63	Low	1.86	Moderate	1.61	30	Moderate
Echinorhinus cookei	28	1.42	Low	1.32	Low	1.61	31	Moderate
Hexanchus griseus	32	1.42	Low	1.32	Low	1.61	32	Moderate
Chephaloscyllium ventriosum	21	1.65	Low	1.82	Moderate	1.58	33	Moderate
Prionace glauca	9	1.5	Low	1.46	Low	1.57	34	Moderate
Alopias vulpinus	30	1.71	Moderate	1.82	Moderate	1.53	35	Moderate
Sphyrna corona	35	1.6	Low	1.5	Low	1.49	36	Moderate
Sphyrna tiburo	38	2.19	Moderate	2.21	Moderate	1.46	37	Moderate
Rhizoprionodon longurio	3	2.19	Moderate	1.86	Moderate	1.18	38	Moderate

The shark species considered in this analysis were moderate (22species) and highly (17 species) vulnerable (Table 10; Figure 5). The species with the highest and lowest vulnerability were *C. leucas* and *R. longurio* respectively (Figure 5). Other species with high vulnerability were *S. lewini, C. obscurus, S. californica, T. semifasciata, G. cirratum, S. mokarran, C. brachyurus, S. zygaena, G. galeus, C. falciformis, I. oxyrinchus, C. galapagensis, N. brevirostris, A. pelagicus, C. longimanus* and *N. velox* (Table 10; Figure 5).

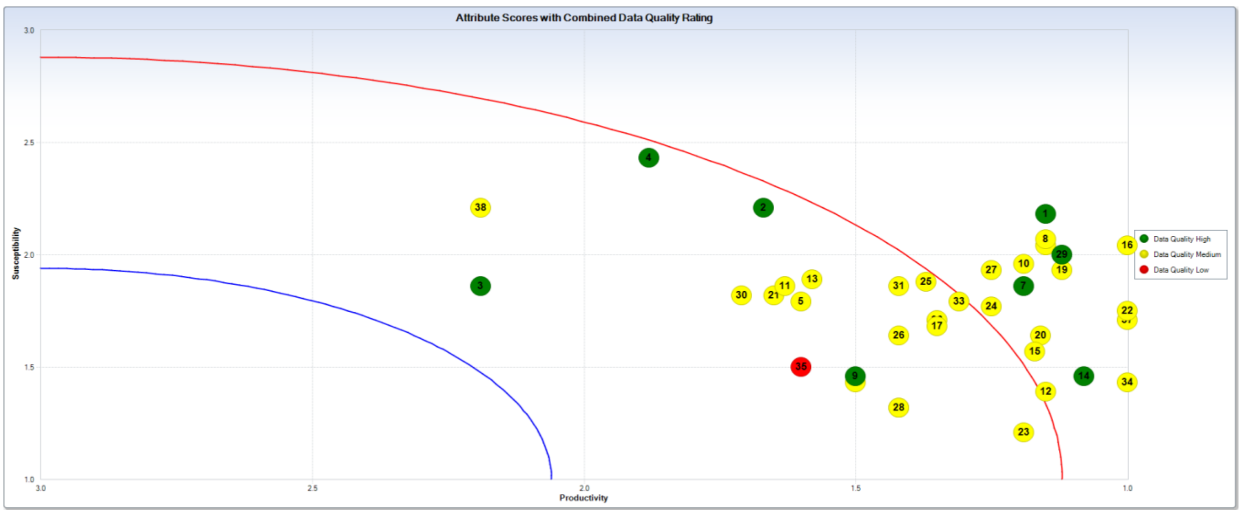


Figure 5. Productivity and susceptibility plot of 38 shark species from the artisanal fishery of the Gulf of California. The upper right corner of the graph is the area of higher risk, while the lower left corner is the lower risk area. Species codes are in Table 1. The isoclines represent the limits of low (blue) and moderate (red) vulnerability

3.3.2 Data quality and sensitivity analysis

The best data quality of the shark species in this analysis was for *Mustelus henlei, P. glauca, M. californicus, S. lewini, I. oxyrinchus, T. semifasciata* and *R. longurio* (18% of all the species). The data quality was medium for 30 species (79%) and low just for one–*S. corona*-(Figure 5). For the productivity attributes, the data quality was low for the 8% of the species, medium for 47% and high for the 45% (Figure 5). The data quality for susceptibility attributes was medium (79%) for the majority of the species, high for seven species (18%) and low for only one species (3%, *S. corona*) (Figure 5). The lowest overall data quality was for two species: *Cephaloscyllium ventriosum*, in the biological aspects–productivity attributes-and *S. corona* in the fishery aspects–susceptibility attributes. For the species *C. ventriosum, N. velox, Mustelus albipinnis, S. corona, S. media, H. griseus, E. cookei* and *H. francisci* there was not much information available of their biology. And for the species *S. corona, S. mokarran, S. media, N. velox, M. albipinnis, C. porosus* and *C. altimus* the majority of the data missing were related with the fishery aspects in relation with the species–susceptibility.

The sensitivity analysis made in this study showed that in a 'best case' scenario, with the lowest scores for F and B, the value of vulnerability decreased for 15 species (39%) and for the 61% of the remaining species the vulnerability values did not changed (Figure 6a). Nevertheless, the change in the category–from high to moderate vulnerability-was only observed in one species: *C. longimanus* (Figure 6a). In the 'worst case' scenario the value of vulnerability increase for all species, and the change from moderate to high category occurred in nine species (*N. cepedianus, M. henlei, H. francisci, S. media, G. cuvier, C. porosus, A. superciliosus, C. altimus* and *M. californicus*) (Figure 6b).

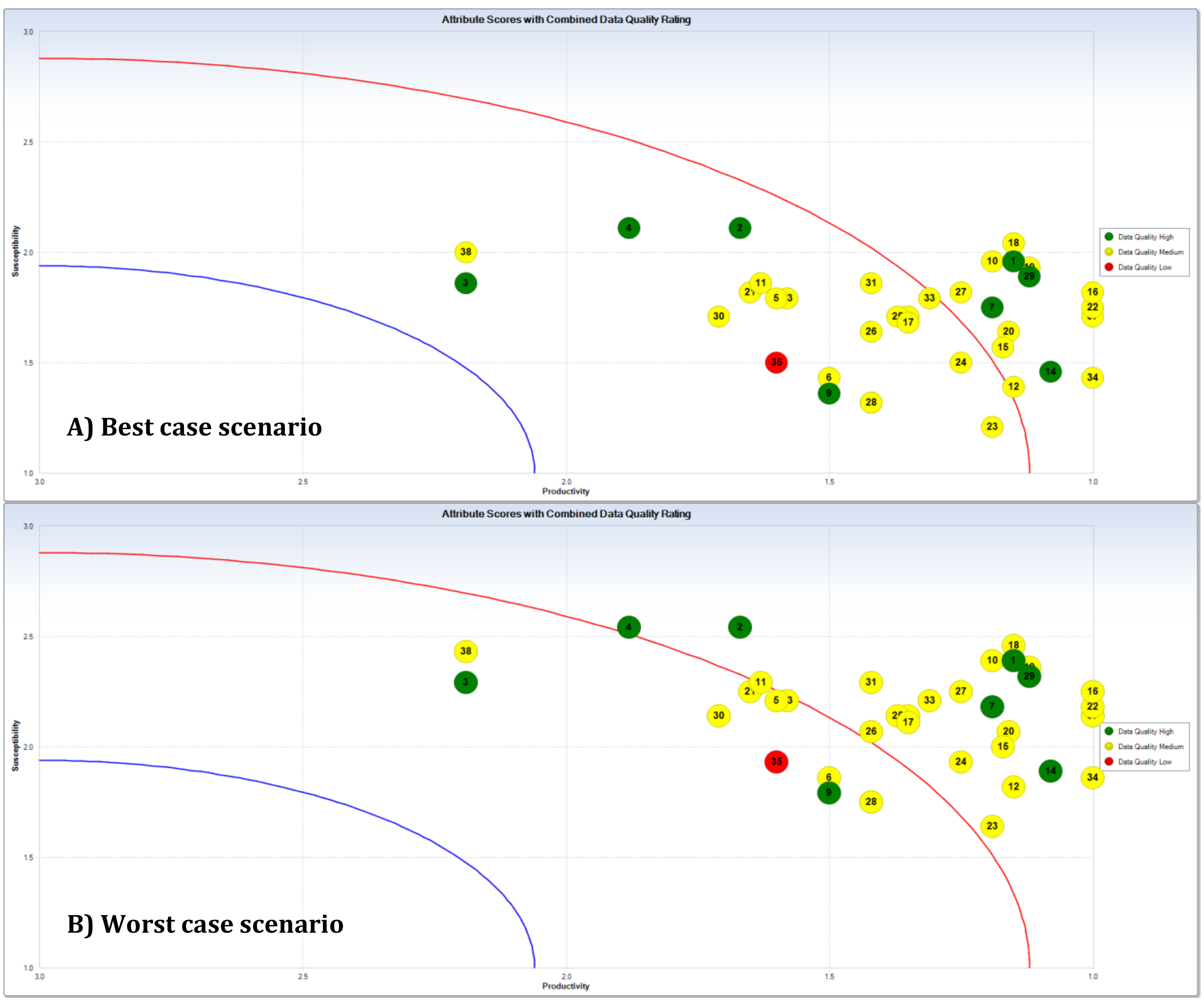


Figure 6. Sensitivity analysis of the PSA. A) Best case scenario: lowest score of fishing mortality rate and biomass of spawners. B) Worst case scenario: high score of fishing mortality rate and biomass of spawners.

3.4. Discussion

3.4.1. Vulnerability of the shark species to the Gulf of California artisanal fishery activities

In the GC the PSA indicates that 17 species were moderate and 21 species highly vulnerable to the fishing. The data quality was high for the 18% and medium for the 79% of the species. The historical context should be considered in order to discuss why some apparently diminished populations of some species are at low risk of overexploitation. More studies on life history traits and, the characterization of the fisheries and their interactions with shark populations are needed in order to improve the PSA analysis and future quantitative assessments for the species more frequent in captures of the artisanal fishery of the GC.

3.4.1.1 Species at high risk to overexploitation

The species *C. leucas, C. obscurus, C. brachyurus, T. semifasciata, N. brevirostris*, *N. velox, G. galeus,* and *G. cirratum* are highly vulnerable to the GC artisanal fishery, mostly due their low productivity. For these species specific biological and fishery data from the GC region, like intrinsic growth rate, growth coefficient, age of maturity, fishing mortality and biomass of the spawners, is still missing; consequently the uncertainty was moderate. These species were historically important in the GC artisanal fishery, in the 1960s and 1970s (Hernández-Carvallo, 1971). Furthermore, *N. brevirostris, G. cirratum,* and *G. galeus* were relevant for the shark fishery since the 1940s for their livers (Hernández-Carvallo, 1971; Berdegue, 1956; Applegate et al., 1979). But in recent years the abundance of these species in the landings is lower, especially for *G. cirratum* and *G. galeus* (Bizzarro et al., 2007, Mondragón Sánchez, 2011, Furlong-Estrada et al., 2014; Sáenz-Arroyo et al., 2005; Applegate et al., 1979). The vulnerability of *C. leucas, C. obscurus,* and *C. brachyurus* to the fishing activities in the GC was documented before; and was suggested a possible overexploitation status for these species (Furlong-Estrada et al., 2014). Also *C. leucas* and *C. obscurus* were described as “fished heavily” since the 1980s (Applegate et al., 1993). Other species, like *G. cuvier, C. altimus*, and *C. porosus* are moderately vulnerable to fishing activities; but also, were more abundant in the landings in the past (Sáenz-Arroyo et al., 2005; Hernández-Carvallo, 1971; Kato, 1965; Applegate et al., 1979).

The hammerhead species, *S. mokarran, S. media, S. corona*, and *S. tiburo* were also more common in the past. *Sphyrna mokarran* in this study is highly vulnerable to the GC artisanal fishery; the high vulnerability of *S. mokarran* was mention in another PSA made in the western and central Pacific Ocean and in the GC (Kirby, 2006; Furlong-Estrada et al., 2014). Moreover, this species is in the category of 'endangered' in the IUCN red list (Denham et al., 2007) and listed in the appendix II of CITES (CITES 2013). In the other hand, *S. media, S. coro*na, and *S. tiburo* are less vulnerable to the fishing activities. Moreover, *S. tiburo* resulted with high biological productivity. This species is abundant and is very important in the fishery in the Bank of Campeche, in the Gulf of Mexico (Cortés and Parsons, 1996; Pérez-Jiménez, 2014a). Also, this species is listed in the IUCN red list as 'Least Concern' due their high abundance and some of the highest population growth rates–productivity-calculated for sharks species (Cortés, 2016). These hammerhead sharks (*S. mokarran, S. media, S. corona*, and *S. tiburo*) were recently described as "extirpated" from the GC, due to the lack of reports in the landings for over two decades (Pérez-Jiménez, 2014b) and their records in the artisanal fishery in the GC are very scarce since the 90s (Saldaña-Ruiz et al. submitted manuscript, 2016a). Nevertheless, the low vulnerability of *S. media, S. corona*, and *S. tiburo* in this study may be due to the following reasons: a) the historical fishery data is not taking into account in the PSA analysis; hence, the vulnerability of the species is estimated under current conditions of the fishing activities. And, b) the data available for these species in the GC is limited, especially for *S. corona*, hence there is a greater uncertainty of the vulnerability estimated.

The historical fishery data of the species could give us hints of their relative exploitation status. For example, in the 1940s these hammerhead species were highly captured for their high quality liver (Berdegue, 1956; Hernández-Carvallo, 1971). Since the 1970s this species were less common, and the historical records of *S. corona* are even scarcer (Applegate et al., 1979). Therefore, the probability of overexploitation of these species, due to the poor regulated shark fishing in the 1940s, was high. Therefore, analyses that estimate current vulnerabilities could mask a more complex status of the species. Also, due to the limited data for these species, were used data for the same species in other regions (e.g. Atlantic Ocean region). Therefore, the vulnerability results could be not reflecting the characteristics of the populations of these hammerheads sharks of the Pacific Ocean; since the life history characteristics of the populations of the same species, located in different regions, may be different, as they are shaped by environmental variations and phylogenetic relationships (Cortés and Parsons, 1996). For all of the above, future research is needed to determinate biological parameters of *S. mokarran*, *S. tiburo, S. media,* and *S. corona* from the Mexican Pacific. Also, besides the global assessment made by the IUCN red list for *S. tiburo, S. corona* and *S. media*, a regional assessment is recommended to identify the population trends by region, which could be useful in regional fishery assessments and management. Finally, an intensive analysis of *S. tiburo, S. mokarran, S. media* and *S. corona* in the artisanal fishery landings of the GC is necessary to clarify their population status.

The evidence of high abundances in the past described above, besides more than five decades under shark fishery exploitation in the GC (Saldaña-Ruiz et al. submitted manuscript, 2016a), and their high and moderate relative vulnerability estimated in the present study, suggest that *C. leucas, C. obscurus, C. brachyurus, T. semifasciata, N. brevirostris, N. velox, G. cuvier, C. altimus, C. porosus, G. cirratum, G. galeus, S. media, S. corona, S. tiburo,* and *S. mokarran* were overexploited in the GC. Consequently, a fully quantitative and more robust analysis must be done to confirm their status and for the developed of the adequate management plans for each species.

3.4.1.2 Species at moderate risk to overexploitation

Another species that resulted with high risk to overexploitation is *S. lewini.* The vulnerability of this species was documented before and was cataloged in the Appendix II of CITES to regulate their international trade (CITES 2013) and, has an "Endangered" status by IUCN red list due to the decline of their populations and high interaction between their aggregations sites and fisheries activities (Baum et.al., 2007). By contrast, a recent study identified *S. lewini* as one of the most important species in the GC artisanal shark fishery for more than seven decades, and it has been suggested that could sustain a fishing pressure, due to a relative stability of the GC population (Furlong-Estrada et al., 201; Saldaña-Ruiz et al., submitted manuscript, 2016a). Despite the high vulnerability of *S. lewini*, the possibility that this species could sustain high fishing pressure could be related with their moderate susceptibility to the fishing activities. *Sphyrna lewini* has a wide-range distribution, compared with other hammerheads (Clarke, 1971), which could reduce their susceptibility to fishing activities by decreasing the area overlap between the fishery and the species distribution. However, it has been described various possible birth and breeding regions for this species in the pacific, including the south of the Mexican pacific and the south of the GC (Clarke, 1971; Alejo-Plata et al., 2006; Salomón-Aguilar et al., 2009), and their overlap with the fishing activities could increase the susceptibility of the species (Bizzarro et al., 2007). A comprehensive study to confirm if the *S. lewini* populations can sustain the artisanal fishery in the GC is urgent. The studies should be focus in the revision of the life history traits of the species, estimation of abundance index, and the analysis of the interactions between the spatial aggregations of the species in the GC and the fishery to evaluate their effect in the population.

Other species with high vulnerability to the GC artisanal fishery were *S. zygaena*, *C. falciformis*, *S. californica*, *C. galapagensis*, and *C. longimanus*. In other study, *S. zygaena* was also described as vulnerable to overexploitation based in their age and growth parameters (Coelho et al., 2011). Besides, this species is described as 'vulnerable' by the IUCN red list (Casper et al. 2005) and is catalogued in the Appendix II of CITES (CITES 2013). *Carcharhinus falciformis* was also described as highly vulnerable to the pelagic longline fishery in the Atlantic by Cortés et al. (2010). Two stock assessments have been conducted for this species; one made in the western and central Pacific Ocean, that conclude that the *C. falciformis* stock analyzed is highly likely to be overfished (Rice and Harley 2013); and the second, made in the eastern Pacific Ocean, in which was indicated that due to lack of data was not possible to estimate the population abundance of this species (Aires-da-Silva et al. 2015). Recently C*. falciformis* was included in the Appendix II of CITES (2016). *Squatina californica* have a "near threatened" status in the IUCN red list (Cailliet et al., 2016); in the region of the pacific coast of Baja California Sur their population is declining (Ramirez-Amaro et al., 2013). By contrast, in the GC this species is frequent in the landings of the artisanal fishery (Smith et al., 2009; Díaz-Uribe et al., 2013). This regional disparity in the frequency of *S. californica* in the landings might be related with possible differences between the GC populations and pacific coast of Baja California Sur (Sandoval-Castillo, 2011). Thus, future studies in a more regional context to evaluate the biology of the populations and the possible differences in the responses to the fishing pressure are needed. *Sphyrna zygaena*, *C. falciformis*, and *S. californica* had been historically important in the GC artisanal fishery with more than four decades of exploitation, and these species are still very frequent in the landings (Saldaña-Ruiz et al. submitted manuscript, 2016a; Bizzarro et al., 2007, Díaz-Uribe et al., 2013). In addition, *S. zygaena* and *C. falciformis* are important in other fisheries, like the pelagic longline fishery in the Mexican Pacific (Galeana-Villaseñor et al., 2009); and *S. californica* is common by catch in the shrimp fishery in the GC (López-Martínez et al., 2010). Hence, attention should be pay to these species to identify or prevent a possible decline in their populations.

In a PSA, regardless of the outcome of vulnerability, susceptibility scores greater than 2.3 indicate a high probability that the species analyzed could be overfished (Patrick et al., 2010). In this analysis, the species *M. californicus* resulted with moderate risk to overfishing, but with the higher value of susceptibility (2.43) among the species analyzed. In a recent study, the historical catch estimation for this species, and other species of the genre *Mustelus* like *M. henlei*, indicates that has supported a fishing effort in the GC since at least the 1960s (Saldaña-Ruiz et al. submitted manuscript, 2016a). Thus, to be certain of the overfished status, a future demographic analysis should be made using specific data of age and growth from the GC (Fajardo Yamamoto, 2014). And, future analysis should also be made for *M. henlei*, another highly susceptibility species with similar biology characteristic than *M. californicus* (Yudin and Calliet, 1990; Pérez-Jiménez, 2006; Mendez-Loaeza, 2008).

The oceanic species *A. pelagicus* and *I. oxyrinchus* resulted with high vulnerability in this study, but with low susceptibility, due to their low interaction with the fishing activities (Ebert et al., 2013). Nevertheless, *A. pelagicus* is more frequent in the landings in the GC than *I. oxyrinchus* (Bizzarro et al., 2007). A study indicate a possible increase in the GC artisanal fishery landings of *A. pelagicus* and *I. oxyrinchus* in recent years (Saldaña-Ruiz et al. submitted manuscript, 2016a), although *I. oxyrinchus,* historically has been described as low abundant in the GC (Hernández-Carvallo, 1971; Applegate et al., 1979). *Carcharhinus galapagensis* and *C. longimanus* were also high vulnerable species to the fishery according to this study. These species are not abundant in landings of the GC artisanal fishery (Bizzarro et al., 2007; Saldaña-Ruiz et al. submitted manuscript, 2016a). However, *C. galapagensis* was a species more frequent in the fishery in the past (Kato, 1965). *Carcharhinus longimanus,* as oceanic species, is less susceptible to the fishery, due to a little area overlap between the artisanal fishing activities and their distribution. However, this species had a 'vulnerable' status by the IUCN red list (Baum et al., 2015) and was recently included in the Appendix II of CITES. For all the above, the monitoring of the *A. pelagicus*, *I. oxyrinchus C. galapagensis,* and *C. longimanus* populations is important to know their status, and for a better understanding of the fishery interactions with these species.

The species *H. mexicanus, H. francisci, C. ventriosum, A. vulpinus, E. cookei, H. griseus,* and *N. cepedianus* resulted moderate vulnerable to the GC artisanal fishery. These species have low relative frequency in the landings of the GC artisanal fishery; and even *A. vulpinus, E. cookei, H. griseus,* and *N. cepedianus* are described as rare and uncommon species (Bizzarro et al., 2007; Applegate et al., 1979; Villavicencio-Garayzar, 1996). Although these species have not been historically important either (Saldaña-Ruiz et al., submitted manuscript, 2016a; Berdegue, 1956; Hernández-Carvallo, 1971; Galvan-Magaña et al., 1989; Applegate et al., 1979; Espinosa-Pérez et al., 2004); should be monitoring to determine their population status.

3.4.1.3 Species at low risk of overexploitation

The species *R. longurio, C. limbatus*, and *P. glauca* are low vulnerable to the fishing activities in the GC. *Rhizoprionodon longurio* is an important species that support the fishery in Nayarit (entrance of the GC), and is abundant in the landings of the GC; furthermore, the GC population is apparently stable (Bizzarro et al., 2007; Pérez-Jiménez et al., 2005; Tovar-Ávila et al., 2011; Furlong-Estrada et al., 2014, 2015; Saldaña-Ruiz et al. submitted manuscript, 2016a). In the other hand, *C. limbatus* is not as common in the landings as *R. longurio*, but both species have supported an intense fishing pressure since the late 1930s (Hernández-Carvallo, 1971; Berdegue, 1956; Saldaña-Ruiz et al. submitted manuscript, 2016a). *Prionace glauca* also had a moderate vulnerability; this species has been described with a relative rapid growth compared with other shark species (Smith et al., 1998). Also, the susceptibility of this species to the GC artisanal fishery is low. This is consistent with other vulnerability analysis in the south of the GC (Furlong-Estrada et al., 2014). And the landings in the GC of these species had apparently increased since 2010 (Saldaña-Ruiz et al. submitted manuscript, 2016a). For all the above is likely that *R. longurio, C. limbatus*, and *P. glauca* can sustain the GC artisanal fishery; however, future fully quantitative analysis are need it to corroborate whether stocks can support the fishery and to estimate optimal extraction levels.

3.4.2. Uncertainty of the analysis

The sensitivity analysis showed greater changes in the PSA results when the attributes were scored with the highest susceptibility values ("worst case" scenario), rather than the lowest values ("best case" scenario). But, all attributes with no information available (including F and B) were scored with the lowest value to not overestimate the resulting vulnerability. And, this explains the little variability in the results of the “best case” scenario.

In the ecological risk assessments, the available information could be very limited, the experts’ consultation is crucial to obtain better results. In this PSA, the knowledge of the experts and stakeholders who participate in the workshops provide sufficient information and valuable discussions and, the general data quality obtained (medium) and the high number of attributes scored (more than 18) reflects this.

The most limited data was mainly for two attributes: fishing mortality rate, in relation to natural mortality, and biomass of spawners; however, the results of the sensitivity analysis indicates that vulnerability result for the absence of these data does not change significantly the results and the possibility that the analysis categorizes species with an erroneous vulnerability is reduced even in cases of very limited data.

3.4.3. Management considerations

Management measures for the GC artisanal fishery should consider the following aspects: life history traits of shark species, characterization of the fishery–fishing gear types, areas, and seasonality of the fishing activities-and, improvement of the official catch records by species.

3.4.3.1. Life history traits of shark species

In this analysis, the shark species productivity evaluation was through their life history traits. The productivity values of the shark species ranged from low (the majority of the species) to moderate, and none of species obtained high productivity. The low productivity of sharks, compared with teleost fishes, has been reported frequently (Camhi et al., 1998; Musick, 1999; Walker, 1998; Stevens, 1999). Nevertheless, in this analysis, is observed a wide range of productivities among shark species; variations that could indicate differences in responses to fishing pressure (Smith et al., 1998). This highlights the need for fisheries management that contemplates the characteristics of each species or at least, considers groups of species with similar response capacities to the fishing. This study provides the firsts insights of these groups through the productivity categories described.

3.4.3.2. Characterization of the fishery

The highest susceptibilities among the analyzed species were for coastal species with a mayor interaction with the artisanal fishery in the GC–e.g. *M. californicus*, *M. henlei*, *S. tiburo*, *S. lewini*, *S. californica*, *C. leucas*, *G. cirratum*, *T. semifasciata* and *S. zygaena* (Santana Morales et al., 2004; Ebert et al., 2013; Bizzarro et al., 2007). While for oceanic and highly migratory species, like *I. oxyrinchus*, *P. glauca* and *A. pelagicus* (Ebert et al., 2013), the susceptibility were low. Cortés et al. (2010) obtained the opposite results; they estimated a higher susceptibility to the pelagic longline fisheries in the Atlantic Ocean for oceanic shark species as *P. glauca* and *I. oxyrinchus* and lower susceptibility for *S. lewini* and *S. zygaena*. These contrasting results are mainly due to the differences in fleet and fishing gear analyzed, while Cortés et al. (2010) described the pelagic longline fishery–industrial scale-, our study was focused in the artisanal fishery–in which bottom set gillnets are the most common fishing gears-(Bizzarro et al., 2007). Thus, future analyses that consider the possible impacts of other fisheries, and specific fishing gears, to the shark species are necessary. Specially in the GC, in which the artisanal shark fishery had regional and seasonal variations in the fishing gear used (Smith et al., 2009; Bizzarro et al., 2009a,b,c), and sharks are captured in other artisanal and industrial fisheries of the region (Bizzarro et al., 2007; Galeana-Villaseñor et al., 2009; Vélez-Marín and Márquez-Farías, 2009). Moreover, shark breeding grounds in the GC has been described for species like *S. lewini, C. limbatus*, *R. longurio*, *C. falciformis*, *S. californica* and *C. obscurus* (Salomón-Aguilar et al. 2009). Therefore, it is important an extensive study of the biology of the species (size structure of neonates and gravid females, seasonal movements and abundance) (Heupel et al., 2007) and the fishing sites in the GC, to identified the overlaps with breeding grounds and have a better understanding of the susceptibility of the species to the artisanal fishery.

3.4.3.3. Improvement of the official catch records by species

One important step to go towards proper management for the shark species of the GC artisanal fishery is the adequate records of the species in the landings. In 2007, as an effort of the Mexican fisheries authorities to improve the biological and fishery data, a national system of scientific information about sharks was implemented through official logbooks, in which are included biological and ecological parameters (DOF, 2007). Also, descriptions by species are available since 2006; nevertheless, these records are mostly in common names and had many errors (CONAPESCA 2016; Saldaña-Ruiz et al.

submitted manuscript, 2016b). Because of this, special attention should be paid to the correct identification of the species and a depuration of the current data base, to start building and accurate history of the species in the GC fisheries. This will be the basis to determine the population status of the species discussed in sections above and for other species in general.

The data necessary for conventional stock assessment is unavailable for many shark species in the GC, and in Mexico, furthermore, would require many years to collect (Bizzarro et al. 2007). In the short term, a rapid assessment, as the PSA, is an alternative to fisheries with data-poor situations as the artisanal fishery of the GC, other fisheries in Mexico and the world. This analysis provides a guide of the urgent needs in information, and priority shark species to focus future research efforts and more quantitative analysis. And is a major effort to lead the way to sustainable GC artisanal shark fishery.

Chapter 4. General discussions

After analyzing the historical shark species landings trends of the artisanal fishery in the GC and the relative vulnerability to fishing by species, I found that species with high vulnerability are identified three groups. The first group includes *S. lewini*, *S. californica* and *S. zygaena*, that have been under fishing pressure since at least 1976, with landings larger than 100 mt per year in the last 10 years and up to 1500 mt in the case of *S. lewini*. The estimated relative vulnerability reflects actual conditions of the fishery (e.g. actual records of fishing areas and gears). The lack of information does not allow the estimation of, for example, Biomass of the Spawners population (adult population) that could give us a hint of the status of the population over the time in this region. A formal assessment is necessary to estimate the level of exploitation and explore specific factors like the allowable fishing mortality, the impact on nursery areas or critical habits for the species (Heupel et al., 2007), the selectivity of the fishing gear in relation with the size at which the removal do not affect the population growth (Simpfendorfer et a., 2005) and if fishing effort does not exceeding a measure of maximum sustainable yield (Gulland, 1968). To assess *S. californica* populations, considerations about the existence of three populations inside the GC and a highly intense fishing pressure in the region have to be considered (Sandoval-Castillo *et al.* 2004; Bizzarro *et al.* 2009; Pérez-Jiménez & Sosa-Nishizaki 2008). For this species, fishermen have reported an abundance reduction over the years (Heist 2004a; Corrigan *et al.* 2008). This trend matches with the landings estimation results of this study, showing a clear decline in landings since 1994.

In the second group, *C. leucas, C. obscurus, S. mokarran* and *C. brachyurus* with low catch estimations but were reported with certain level of exploitation in the GC (Applegate et al., 1993; Furlong Estrada et al., 2014). Besides the high vulnerability, there is a lack of specific data for these species in the GC in important attributes like the Intrinsic growth rate, growth coefficient, age of maturity and area overlap, the last one related to the limited information of the delimitation of the stock for these species.

Finally a third group of species (*T. semifasciata, G. cirratum* and *G. galeus*) of which there are no historical records that mention their relative importance in the fishery in the GC (Applegate et al., 1979; Compagno, 1984; Castillo-Géniz et al., 1996; Bizzarro et al., 2007; Mondragón Sánchez, 2011), and the catch estimation for these species are less than 9 mt per year in the last ten years. In other study *G. cirratum* were reported with moderate vulnerability to the fishery in the entrance of the GC (Furlong

Estrada et al., 2014), the high vulnerability in this study could be due the greater extension of fishing area analyzed resulted in a greater susceptibility of this species, additionally, the are some missing data for this species in the GC (intrinsic growth rate, growth coefficient, age of maturity) and also in the red list of the IUCN is in the category of Data Deficient (Rosa et al., 2006). There are also missing data for *G. galeus* in the GC region, which is important to consider due the possibility of spatial variations in size structure between populations (Walker, 1999) since has been reported differentiation in the genetic structure between six population worldwide (Chabot and Allen, 2009); moreover, susceptibility aspect like an overlap between the fishery activities and possible nursery areas in the GC should be revised, considering that has been described for this species nursery areas in shallow bays and estuaries in other regions like Australia and Southern California bay (Olsen, 1954; Walker et al., 2006), and also their current status as vulnerable by the red list of the IUCN by a decreasing tendency of the population (Walker et al., 2006). Finally for *T. semifasciata* the historical catch estimation show a decline in the catches in the GC since 1980, but the catches not exceed the 3.8 mt in all the period estimated (from 1976 to 2012), contrary to this, this species is reported as one of the most common elasmobranch in California, USA (Ebert and Ebert, 2005), and as a result of the studies take place in that region it was possible to have information for productivity aspects, however, more information of the region of the GC is need to enhance the PSA analysis of this species. Due to the above, is necessary to pay extra attention to these species to clarify their population status in the GC.

The species with the lowest levels of vulnerability in this analysis were *R. longurio*, *S. tiburo* and *S. corona*. The moderate productivity (high productivity considering only the sharks species analyzed here) of *R. longurio* make this species less vulnerable of all the species analyzed although their susceptibility is moderate and is one species with high historical catches estimated, just in the last 10 years the average catch per year was 830 t; in the region of Nayarit, in the GC, this species also result with moderate vulnerability to the artisanal fishery and due their constant presence in this fishery over the years it has be suggested the possibility of sustain high levels of catches (Saucedo Barrón, 1982; Pérez-Jiménez et al., 2005; Tovar-Ávila et al., 2011; Furlong Estrada et al., 2014) nevertheless, is necessary an extensive study, that include all the GC region, to determinate levels of fishery exploitation, since still missing some important biological and fishery data like intrinsic rate, fishing mortality, biomass of the spawners and CPUE.

In the case of *S. tiburo* and *S. corona*, their moderate productivity and low susceptibility, respectively, place them in moderate vulnerability to the artisanal fishery, but these species are reported as uncommon in the landings in the GC (Bizzarro, et al., 2007) and along with *S. media* and *S. mokarran* are described as potentially extirpated in the Mexican pacific, this based in the analysis of historical records were these species are absent from the landings since the 90´s (Pérez-Jiménez, 2014), this is also reported for Furlong Estrada et al., 2014 in the south region of the GC and in this study the historical catch estimation it could not be accomplish at the species level, the species mention above were grouped into *Sphyrna* spp. and still, the catches for this group were below the 25 mt for all the period (1976-2012). For *S. corona* the DQ were poor due the lack of many biological and fishery data, because of this, it should be consider getting more information of the species to clarify their level of vulnerability to the fishery. The DQ for *S. tiburo* was better; nevertheless, many of the information used were from another region (Mostly Gulf of Mexico) because of the lack of data for this species in the GC or even in the Pacific, because of this, it was expected the similarities between this study and another made in the Gulf of Mexico, in which the vulnerability for this species was also moderate, plus, is described their capacity of support the fishery of the region for many years (since the 80´s) (Pérez-Jiménez et al., 2012; 2014); is necessary to improve the data for this species in order to identify if there are a possible demographic distinction in the life history traits (Cortés, 2002) (e.g. different population between the Pacific and the Atlantic), and if this differences could cause the variation in the vulnerability of this species to the fishery activities in the GC and the Gulf of Mexico.

The ecological risk assessment only provide the relative vulnerability of the species under current conditions, because it used the recent biological data and the actual dynamic of the fishery analyzed and is not possible to infer in historical changes in the species populations (Griffiths et al., 2006; Cortes et al., 2009; Furlong Estrada et al., 2014), in the Patrick et al. (2010) methodology of the PSA, there is an attribute, Biomass of the spawners, that attempt to infer in the depletion of the fishery over the time, but for any sharks species in the GC there are not data available. Due the above, were consider the catch estimation made in this study, to provide more knowledge of the species besides of their relative vulnerability (Walker, 2007) and with this provide more information of the artisanal fisheries in the GC, the vulnerability of species to become overfished, the major historical trends and the needs of further research.

Chapter 5. General conclusions

The artisanal shark fishery of the Gulf of California contributed with an average of 36% of the national shark production for the period from 1939 to 2014 with a maximum catch estimated in the Gulf of California of 17,531 mt in 1979.

The catch composition in the artisanal shark fishery has shown little changes through the years for some of the species. The taxa with constantly high landings over the estimated period estimated (1960-2014) were *Mustelus spp., S. lewini, R. longurio, S. californica, C. falciformis, S. zygaena, C. limbatus, N. velox, A. pelagicus* and *H. mexicanu*s. Species that were reported as important in the past, with high historically presence in the fishery of the GC but with recent few reports or that are catalogued as uncommon or rare, are: *C. brachyurus, C. porosus, G. cuvier, G. cirratum, C. obscurus, C. galapagensis, T. semifasciata, S. media, S. mokarran* and *S. tiburo.*

The majority of the shark species showed a declining trend in their landings since 1979, been the most notorious *S. lewini, Mustelus spp., R. longurio, C. leucas, C. brachyurus*, *Sphyrna spp., G. cuvier* and *C. cirratum*. However, *G. cuvier* and *C. cirratum* have shown an increase trend in their landings since 2006. And *P. glauca* landings have increased since 1994, especially in relations with the development of the middle size vessel fishery based at Mazatlán port.

All the shark species analyzed resulted with low to moderate productivity, however, among the analyzed these species; I found more productive species than others. However, among the species there are a variety of life history traits that should be taken into account when establishing management measures.

The susceptibility of most species was moderate, which reflects that fishing activities do not exert much pressure on these species, but the information available to assess the susceptibility was limited and were used some assumptions to define the distribution of stocks. Therefore the consultation and discussions with experts was very important to assign the final scores. However, it was clear that still more effort is need it to understand the biology and fisheries impacts on several of the species.

The relative vulnerability of all the shark species was from moderate to high, and even when for some species their susceptibility was low, the low productivity was a determinant factor in the vulnerability obtained. The most vulnerable species were: *C. leucas, S. lewini, C. obscurus, S. californica, T.*

semifasciata, G. cirratum, S. mokarran, C. brachyurus, S. zygaena and *G. galeus*, thus, future studies in management and conservation should be for these species, it should also be included species (*N. brevirostris, N. velox, G. cuvier* and *C. ventriosum*) with a moderate vulnerability but have a very low productivity, scarce information available and declines in the catches estimated.

The most limited data was mainly for two attributes: fishing mortality rate, in relation to natural mortality, and the level of spawners biomass. However, the results of the sensitivity analysis indicate that the vulnerability results with the absence of these data do not change significantly the results.

The less vulnerable species were *R. longurio, S. tiburo, S. corona, A. vulpinus* and *P. glauca. Sphyrna tiburo* was one of the most productive species, but, along *with S. media, S. corona* and *S. mokarran*, should be monitored and are necessary studies to clarify its population status in the Gulf of California due to their probable absence in landings since the 90's. This situation highlights the importance of including historical analyzes of the catches to identify priority species for future research efforts.

The analysis made in this study (PSA) does not replace a formal stock assessment, however, this rapid analysis provide guidance of where to start to improve the biological and fishery data and for which species and is a first evaluation of the primary issues of the artisanal shark fishery in the Gulf of California.

Recommendations

Future research efforts to evaluate the status of shark species populations should focus on relative high vulnerable species, e.g. *C. leucas, S. lewini, C. obscurus, S. californica, T. semifasciata, G. cirratum, S. mokarran, C. brachyurus, S. zygaena* and *G. galeus*. The species with low productivity and very limited information available, *N. brevirostris, N. velox, G. cuvier* and *C. ventriosum*; and species populations that have been apparently extirpated in Mexican Pacific, *S. tiburo S. media, S. corona* and *S. mokarran* should be taken as an example for future comparison, and their fishing history should be more deeply analyzed.

Given the variety of life history characteristic for the group of analyzed species, it is important to collect biological data and detailed description of the species that are present in the landings. Monitoring of the fishing activities to measure the applied fishing effort and estimates of fishing mortality and natural mortality should be encourage to provide elements for a more robust population assessment.

Future management strategies must be developed to species level, to achieve this, besides the stock assessments by species, a clear delimitation of the stocks, either through genetic or morphometric studies are need. Also, a more precise description of the spatial distribution of the species through fishery independent surveys (e.g. tagging studies) and actions to identify sharks essential habitats (e.g. nursery areas) should be taken. Fishing gear selectivity to has to be estimated for the main fishing gears used in the GC shark fisheries, in order to interpret the size and age structure of the landings, in the context of age of maturity or other vulnerable stages of the species.

Studies of the oceanographic features of the Gulf of California in relation with the shark species distributions is very relevant to identify possible effects on the distributions and abundance of the species. It will be helpful to understand how large-scale phenomena like El Niño and La Niña can affect sharks populations, as well as to understand the potential effects of climate change on these populations.

Finally, the PSA analysis must be constantly updated as new information is generated in order to clarify the relative vulnerability of the shark species. Also, the evaluation should be made for different fisheries and regions in Mexican waters in order to have a more comprehensive picture of the vulnerability of the shark species to avoid overexploitation of shark populations in this country.

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