Identification of a nursery area for the critically endangered hammerhead shark (Sphyrna lewini) amid intense fisheries in the southern Gulf of Mexico

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Identification of a nursery area for the critically endangered hammerhead shark (*Sphyrna lewini*) amid intense fisheries in the southern Gulf of Mexico

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Abstract

Since the 1980s, there has been growing concern in the Mexican Atlantic regarding high catches of neonate and juvenile sharks in small-scale fisheries. Fishery-dependent data from 1993 to 1994 and 2007 to 2017 and fishers' ecological knowledge from 2017 were used to identify nursery areas for scalloped hammerhead, *Sphyrna lewini*, in the southern Gulf of Mexico. Catch records and fishing areas of neonates, YOYs, juveniles and adults of *S. lewini* (N = 1885) were obtained from calcareous and terrigenous regions in the western Yucatan Peninsula. The results suggest that a nursery for scalloped hammerhead is found in the terrigenous region, characterized by relatively shallow and turbid waters due to rivers' discharges. Neonates and YOYs (96% and 86% of their total records, respectively) were commonly found there over the years in May–August in multiple fishing areas identified by fishers, although mainly between isobaths 10–30 m. The enforcement of management measures is necessary because the nursery is located in a region with intense fishing effort.

KEYWORDS

fishers' knowledge, fishery management, hammerhead shark, nursery habitat, small-scale fisheries

1 | INTRODUCTION

In Mexican waters of the Gulf of Mexico, there has been growing concern since the 1980s regarding high catches of neonate and juvenile sharks in small-scale fisheries (Bonfil, 1997; Castillo-Géniz *et al*., 1998; Pérez-Jiménez & Méndez-Loeza, 2015). In the southern Gulf of Mexico, neonates and juveniles of at least nine shark species, including the scalloped hammerhead, *Sphyrna lewini* (Griffith & Smith 1834), were frequently caught in the 1980s and 1990s (Bonfil, 1997; Bonfil *et al*., 1990).

Nursery areas for some carcharhinid and sphyrnid sharks have been documented in Mexican waters of the Gulf of Mexico and the Caribbean Sea using fishery-dependent data (Applegate *et al*., 1993; Bonfil, 1997; Bonfil *et al*., 1990; Castillo-Géniz *et al*., 1998) and fishery-independent data (Hueter *et al*., 2007). The Mexican Official Standard NOM-029-PESC-2006 (D.O.F., 2007) established temporal closed seasons for the protection of elasmobranch neonates off Playa Bagdad (western Gulf of Mexico), Delta of the Grijalva-Usumacinta system and Terminos Lagoon (southern Gulf of Mexico), Yalahau Lagoon (northeastern Yucatan Peninsula) and Espiritu Santo, Ascension and Chetumal Bays (Caribbean Sea). Unfortunately, these shark nursery areas are also important fishing grounds. Neonate sharks are caught mainly using gillnets, which is the gear used to capture profitable teleost species (Castillo-Géniz *et al*., 1998).

1.1 | Nursery areas of *S. lewini*

It is well known that there is spatial segregation between the life-history stages of *S. lewini*, where neonates and young juveniles spend the first part of their lives in coastal waters, whereas older juveniles and adults move to open ocean, returning to the nursery areas for parturition (Clarke, 1971). Previous studies indicated that *S. lewini* uses nursery areas located in shallow and turbid waters (Clarke, 1971; Duncan & Holland, 2006; Yates *et al*., 2015). Probably the most studied nursery of this hammerhead is Kāne'ohe Bay, Oahu, Hawaii (Bush, 2003; Bush & Holland, 2002; Clarke, 1971). Other nurseries of this species have been documented in Carolina coast, eastern United States (Castro, 1993), and Florida (Adams & Paperno, 2007), and there is some evidence of a nursery in the northern Gulf of Mexico (Parsons & Hoffmayer, 2007). In Mexican Atlantic waters, Bonfil (1997) recorded neonates of *S. lewini* off the central coast of Veracruz and in waters adjacent to Laguna Madre, Tamaulipas (western Gulf of Mexico), and to Laguna de Terminos (southern Gulf of Mexico).

1.2 | The use of fishery-dependent data and fishers' ecological knowledge

Generally, the use of fishery-independent surveys is more robust to identify nursery areas (Heupel *et al*., 2007); nonetheless, as established by Springer (1967), landing records can provide information on the social organization of sharks (*e.g*., spatial and temporal distribution of life-history stages). The use of fishery-dependent data for scientific research offers many benefits such as long time series; large spatial coverage; and information on a variety of target species, fishing gears and fishing areas (Lunn & Dearden, 2006). In addition, sometimes fishery-dependent surveys are the only data available in some regions (Fox & Starr, 1996; Pennino *et al*., 2016). Thus, fishery-dependent data and fishers' ecological knowledge can be used to identify essential fish habitats, such as nursery areas, when fishery-independent data are limited (Bergmann *et al*., 2005; Serra-Pereira *et al*., 2014).

The aim of this study was to describe temporal and spatial occurrences of life-history stages of *S. lewini* in the southern Gulf of Mexico using fishery-dependent data and fishers' ecological knowledge to identify areas used potentially as a nursery.

2 | MATERIALS AND METHODS

2.1 | Ethical statement

In this study no experiments with animals were performed. Scalloped hammerheads were collected as part of fishery-dependent surveys. Therefore, all examinations were made upon deceased animals that were captured during legal commercial fishing operations.

2.2 | Study area

The landing records of *S. lewini* were obtained from Campeche (western Yucatan Peninsula) and Tabasco States (Figure 1). The coast of Campeche belongs to the Campeche Bank, a continental shelf with significant width extending as far as 216 km offshore (Gío-Argaez *et al*., 2002) narrowing westward along the Mexican coast (Yáñez-Arancibia & Day, 2004), including Tabasco, that borders Campeche.

The western Yucatan Peninsula is divided by the Champotón River, in the central coast of Campeche, in a region without rivers and reef areas to the north and a region with rivers and oil platforms to the southwest. The presence of rivers causes a shelf sedimentation transition from calcareous to terrigenous at Terminos Lagoon (Kemp *et al*., 2016) (Figure 1). Thus, the authors divided the catch records of *S. lewini* in the calcareous region (Region 1) and terrigenous region (Region 2).

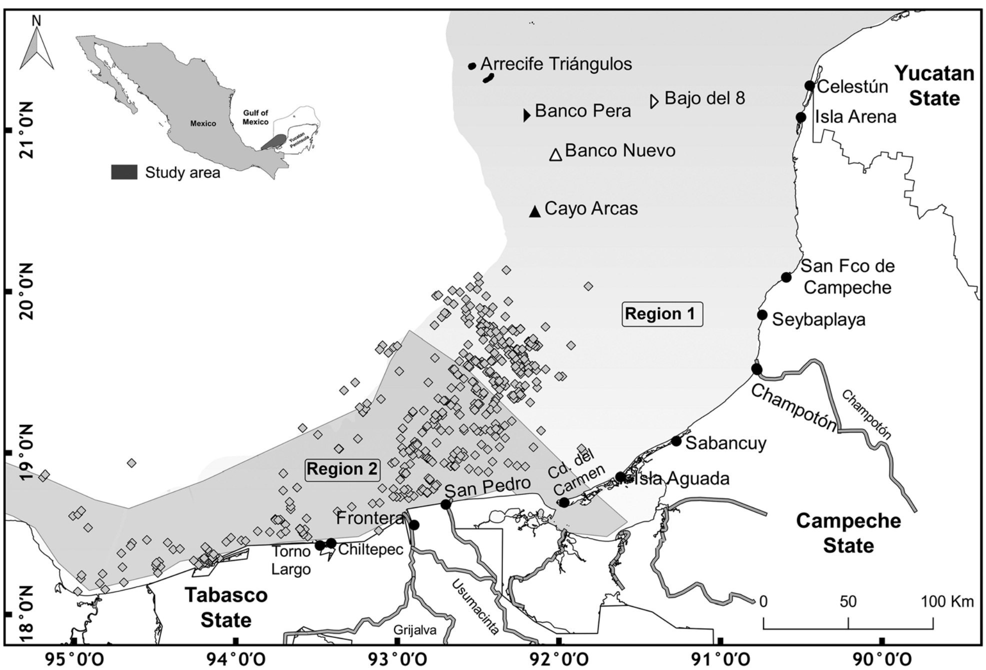

FIGURE 1 Study area in western Yucatan Peninsula, southern Gulf of Mexico: locations of fishing ports (black circles), oil fields (every diamond is an oil platform), reef areas (triangles and circles in the shelf) and the calcareous (Region 1) and terrigenous (Region 2) regions with its transition at Terminos Lagoon. (Legend: ▭ Rivers; ▭ Calcareous; ▭ Terrigenous; ◇ Oil platforms)

2.3 | Fishery-dependent data

The monitoring programme was carried out by trained biologists from the National Fisheries and Aquaculture Institute (INAPESCA, acronym in Spanish) in the period 1993–1994 and from the Fisheries Ecology Laboratory of El Colegio de la Frontera Sur (ECOSUR, acronym in Spanish) in the period 2007–2017.

Fishery-dependent data were obtained from landings along 35 fishing ports in the states of Tabasco, Campeche and Yucatan from 2007 to 2017 (N = 746 days of monitoring effort) in 18 fisheries described by Pérez-Jiménez and Méndez-Loeza (2015), including target fisheries for small sharks (N = 1), large sharks (N = 3), rays (N = 2), teleost fish (N = 11) and shrimp (N = 1). All fisheries have multiple by-catch species, including *S. lewini* in the fisheries for small sharks, rays and teleosts. The monitoring effort was not similar through the years, with the most intense effort occurring in 2008, 2012 and 2016. Data collected during 1993–1994 included only Campeche (N = 200 days of monitoring effort). Standardization of landing records was not possible due to the variability of the fishing effort, fishing areas, target species and gears used; sometimes fishers alternate at least two gears in a single fishing trip (Pérez-Jiménez & Méndez-Loeza, 2015).

A sub-set of the scalloped hammerheads landed were measured to the nearest centimetre, using total stretched length (L_T) on a horizontal line between perpendiculars, from the tip of the nose to the tip of the caudal fin (Compagno, 1984). The number of sharks measured depended on the landing process; sometimes it was possible to measure all sharks, but other times it was possible to measure only a sub-sample of at least 30% of the sharks landed. Sex was determined macroscopically according to the presence or absence of claspers on the pelvic fins. Sharks were classed as (a) neonates, when they had unhealed or healing umbilical scar (Castro, 1993); (b) YOYs, when they had a healed umbilical scar and belonged to the first year according to the von Bertalanffy growth curve by Piercy *et al.* (2007); (c) juveniles, when they were older than a year and were not yet sexually mature; and (d) adults, in males when they had calcified claspers (Clark & von Schmidt, 1965) and females when they met the criteria of the first ovulation according to Walker (2005) and Pérez-Jiménez and Sosa-Nishizaki (2010). There were few records of adult females in this study to estimate the size at maturity; therefore, females that were not dissected were classified as mature if they were greater than 245 cm in total length (Castro, 2011).

The number of scalloped hammerheads by life-history stages was compared by years, months and regions. Independence tests were conducted to determine if neonates, YOYs and juveniles were independently distributed between regions and if they were independently recorded between 4 month periods (first: January–April, second: May–August, and third: September–December).

2.4 | Fisher´s ecological knowledge

A second source of information was obtained by semi-structured interviews in 2017. Interviews were conducted with fishing boats' captains (N = 19, age range 25–80 years) from San Francisco de Campeche port (Region 1) and with fishing boats' captains (N = 25, age range 23–66 years) from San Pedro port (Region 2). In both ports, 86% of fishers had at least 10 years of fishing experience. The interview questions are as follows: Which are the fishing areas for scalloped hammerheads? What is the size or weight of the specimens? Where do you catch the different size classes of specimens? A map with reference points, such as coastline, fishing ports, isobaths, reef areas and oil platforms, was included in the interview. Each fisher identified multiple areas in the map where they have fished life-history stages of scalloped hammerheads. Maps were made by using the Google Earth Pro app and the programme Qgis 2.18.3. to locate the fishing areas by life-history stage.

2.5 | Identification of nursery areas of *S. lewini*

To determine if the nursery areas of *S. lewini* occur in the southern Gulf of Mexico, the occurrences of neonates, YOYs and juveniles in landing records were compared by year and month in each region. In particular, the records of neonates and YOYs were used to determine if a region met the criteria of a nursery area according to Heupel *et al.* (2007). The three criteria proposed by Heupel *et al.* (2007) for neonates and YOYs to define nursery areas are that (a) sharks are more commonly encountered in the specified area than in other areas, (b) sharks tend to remain or

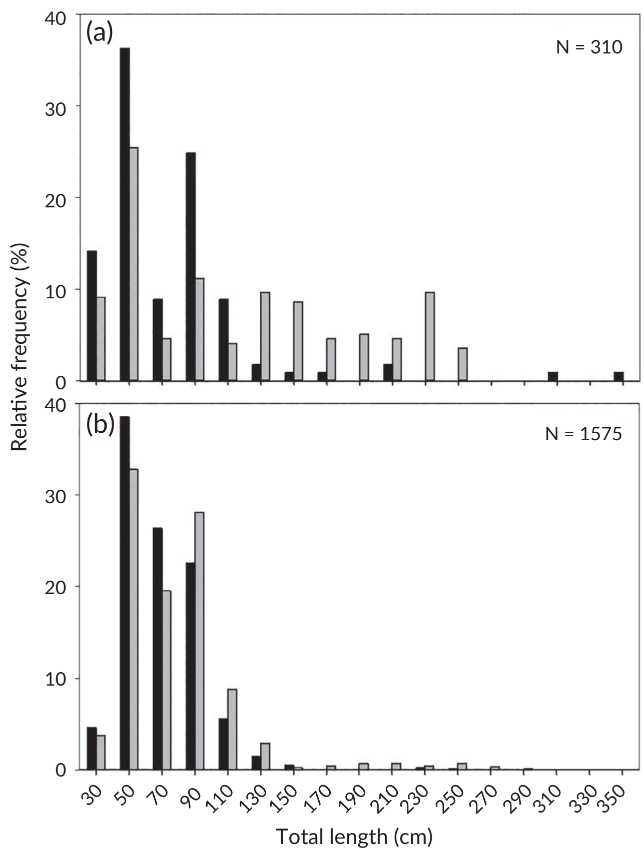

FIGURE 2 Size structure of *Sphyrna lewini* in the two-fishery-dependent sampling periods (a) 1993–1994 and (b) 2007–2017. (■ Females and □ Males)

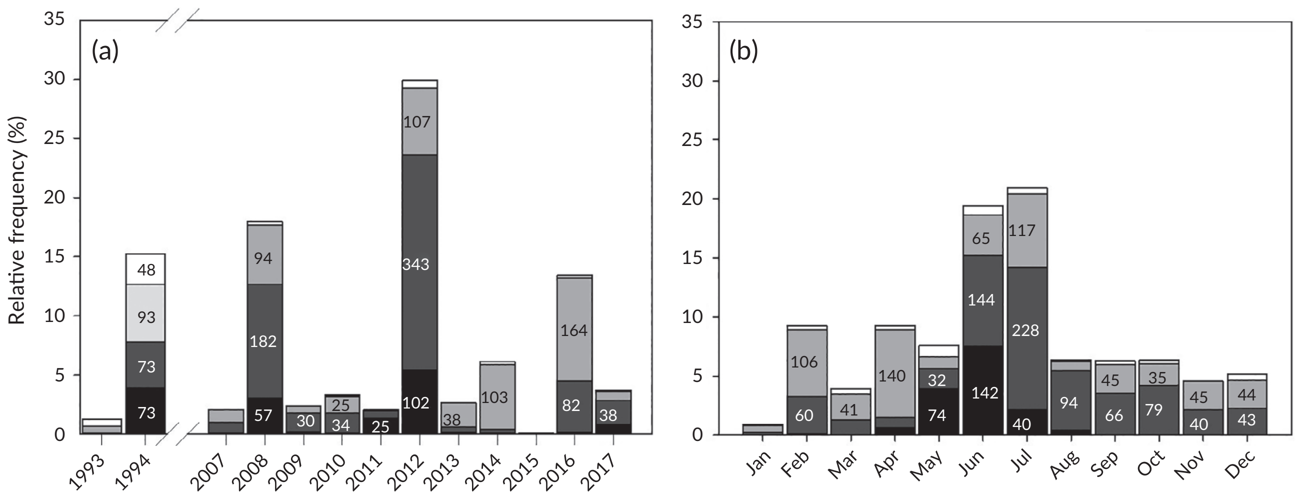

FIGURE 3 Relative frequency of life-history stages of *Sphyrna lewini* by (a) years and (b) months. Ne = neonate, YOY = young-of-the-year, J = juvenile and A = adult. The number of records (>25) per stage is shown in the bar. (■ Ne; ■ YOY; ■ Juv; □ A)

return for extended periods and (c) the area or habitat is used repeatedly across years. The maps with fishing areas for neonates and YOYs were used as a second source of evidence.

3 | RESULTS

3.1 | Description of the fishery

Fishers operated small outboard motor boats 7.5–9 m in length, which were made of fibreglass, and some small inboard motor boats 8–10 m in length, which were made of fibreglass or wood. Fishers used a variety of gillnets (mesh-size 4–38 cm) or longlines (circle and straight-shank J hooks 2.5–8 cm in length) in fishing trips that last 1–5 days, depending on the target species.

The landings of *S. lewini* occurred in a limited number of fishing ports (out of a total of 35), San Francisco de Campeche, Seybaplaya, Champotón, Sabancuy, Isla Aguada, Ciudad del Carmen, San Pedro and Frontera (Figure 1). Most of the records belonged to the target fishery for small sharks and mackerels from San Francisco de Campeche port (Region 1), which used gillnets of nylon with a mesh-size of 11.5 cm, and to the fisheries for gafftopsail sea catfish/stingray and snappers from San Pedro port (Region 2), which used longline with circle hooks 4.5 and 3–3.5 cm in length, respectively. The fishing area of fishers targeting snappers is far from San Pedro port, reaching the edge of continental shelf and reef areas in the calcareous region (Figure 1).

3.2 | Size structure and temporal records

A total of 1885 scalloped hammerheads were recorded, 310 from 1993 to 1994 (Figure 2a) and 1575 from 2007 to 2017 (Figure 2b). The size range of females and males was 42–354 cm L_T and 35.5–300 cm L_T, respectively. The size of neonates was 35.5–57 cm L_T (N = 279), YOYs 54–93 cm L_T (N = 830), juveniles 87–178 cm L_T (N = 683) and adults

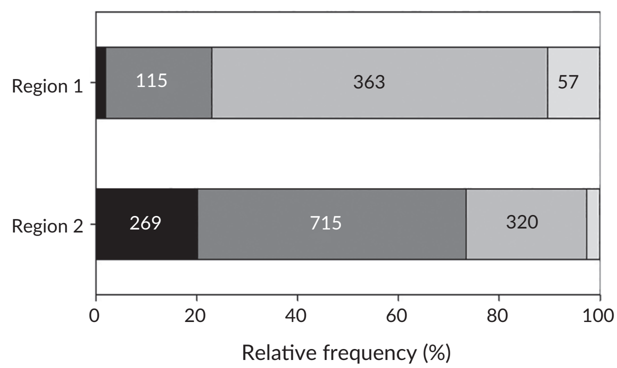

FIGURE 4 Relative frequency of life-history stages of *Sphyrna lewini* in Region 1 (calcareous) and Region 2 (terrigenous). Ne = neonate, YOY = young-of-the-year, J = juvenile and A = adult. The number of records per stage is shown in the bar. Records of Ne in Region 1 = 10 and A in Region 2 = 36. (■ Ne = 279; ■ YOY = 830; ■ Juv = 683; □ A = 93)

169–354 cm L_T (N = 93). Most of the records were obtained in the years with the highest monitoring effort (1994, 2008, 2012 and 2016) (Figure 3a). The highest neonate records occurred in May and June (77%); YOYs records in June, July and August (56%); and juvenile records in February, April and July (53%) (Figure 3b).

3.3 | Life-history stages of *S. lewini* by region

A total of 545 scalloped hammerheads were recorded in Region 1. Juveniles accounted for the majority of records (N = 363, 66.5%), followed by YOYs (N = 115, 21%). In Region 2 were recorded 1340 scalloped hammerheads. YOYs were the most frequently recorded (N = 715, 53%), followed by juveniles (N = 320, 24%) and neonates (N = 260, 20%) (Figure 4). Records of every stage are dependent on regions (X^2 = 384, P < 0.0001); 96% and 86% of neonates and YOYs

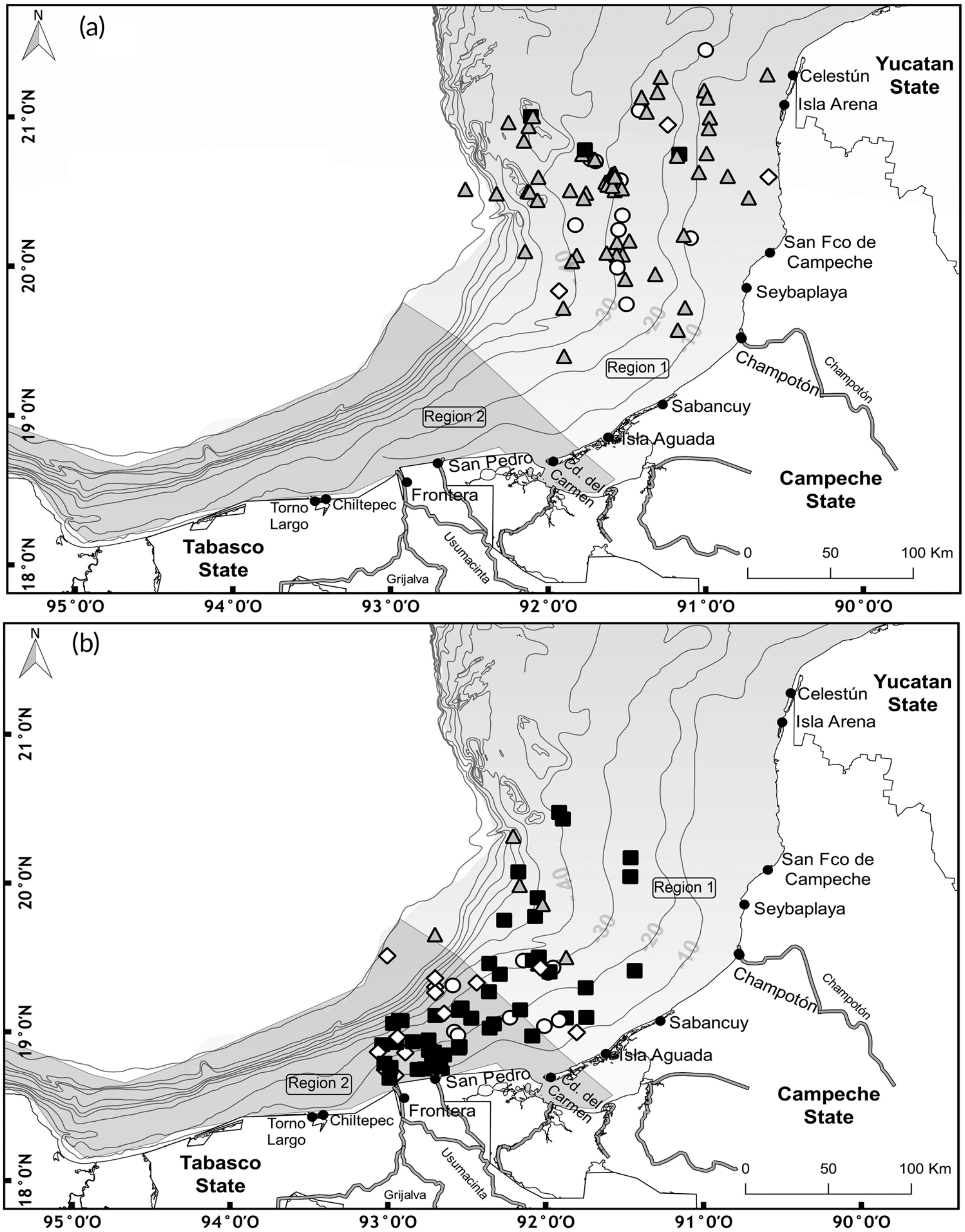

FIGURE 5 Fishing areas for life-history stages of *Sphyrna lewini* identified by fishing boat captains from (a) San Francisco de Campeche port and (b) San Pedro port. Each dot represents a fishing area where fishers have caught a particular life-history stage. The transition between the calcareous (Region 1) and terrigenous (Region 2) regions is shown. (Life-history stages: ■ Neonate; ○ YOY; △ Juvenile; ◇ Adult)

were recorded in Region 2, and 53% and 61% of juveniles and adults were recorded in Region 1, respectively.

Fishers interviewed from San Francisco de Campeche port (Region 1) target seasonally small sharks or mackerels with gillnets from coastal to reef areas (Figure 1), between Champotón to Isla Arena ports, where they identify multiple fishing areas in which scalloped hammerheads are caught (Figure 5a). All fishers indicated that juveniles are very common in their captures and that YOYs are the second most common specimens. The fishing areas with the highest mentions by fishers occur off Isla Arena port between isobaths 10–30 m and off San Francisco de Campeche and Seybaplaya ports between isobaths 30–40 m. Fishers interviewed from San Pedro port (Region 2) target gafftopsail sea catfish/stingray and snappers with longlines, from Frontera port to the northeast, into the Campeche Bank, where they identify multiple fishing areas in which scalloped hammerheads are caught (Figure 5b). All fishers indicated that neonates and YOYs are very common in their captures and mentioned that they occasionally caught gravid females in the same coastal areas where neonates and YOYs are caught. The fishing areas with the highest mentions by fishers occur from Frontera port to Isla Aguada port between isobaths 10–30 m.

3.4 | Life-history stages of *S. lewini* by four month periods and years

Neonate and YOY records are less frequent in Region 1 than in Region 2 over the months (Figure 6a,c). From the total records of each

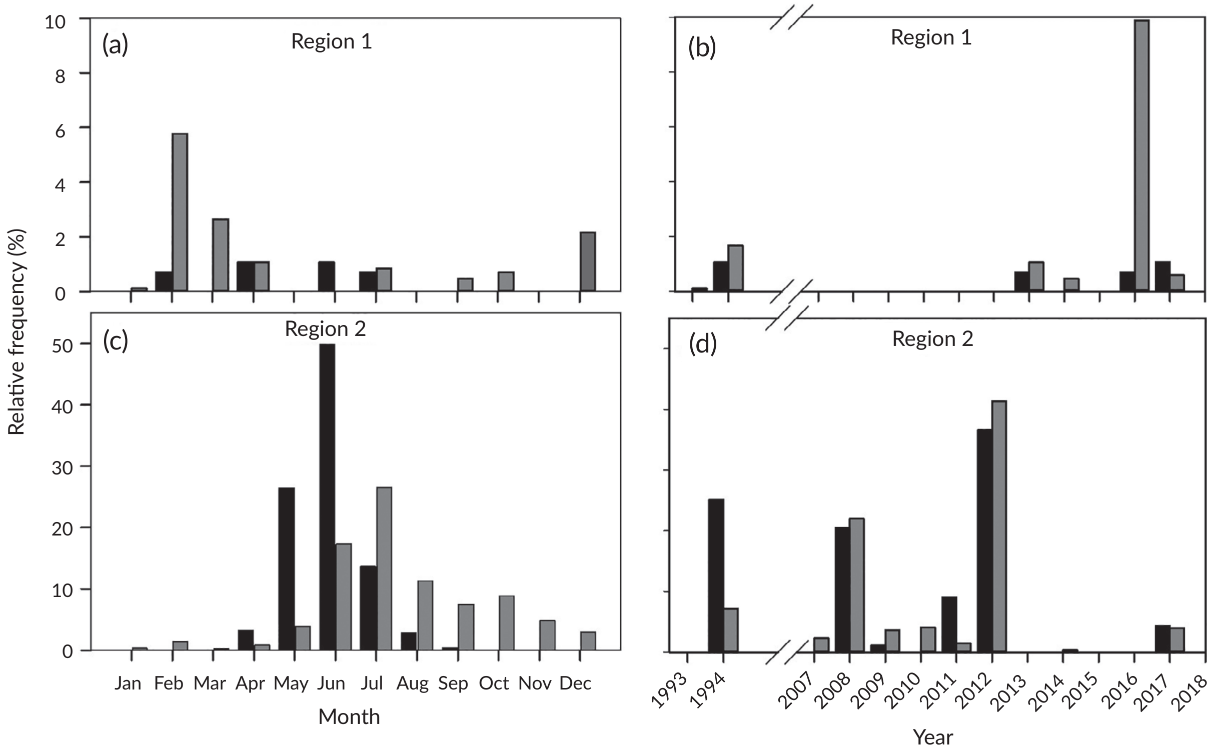

FIGURE 6 Relative frequency of neonates (Ne) and YOY of *Sphyrna lewini* by (a) month and (b) year in Region 1 and by (c) month and (d) year in Region 2. The total records (100%) of each stage are the sum of percentages from both regions by months (a and c) and years (b and d). (■ Ne = 279 and ■ YOY = 830)

life-history stage including both regions, Region 1 had only 3.5% and 14% of records of neonates and YOYs, respectively (Figure 6a). In Region 1, the records of neonates (*N* = 10) occur in the first and second 4 month periods (50% each), YOYs (*N* = 115) had the highest records in the first 4 month period (70%) and juveniles (*N* = 363) had the highest records in the first and second 4 month periods (52% and 35%, respectively). The records of the life-history stages in Region 1 are dependent on 4 month periods (X^2 = 42.1, *P* < 0.0001).

From the total records of each life-history stage including both regions, Region 2 had 96.5% and 86% of records of neonates and YOYs, respectively (Figure 6c). In Region 2, the records of neonates (*N* = 269) and YOYs (*N* = 715) were more frequent in the second 4 month period (96% and 69%, respectively); YOYs had 28% of the records in the third 4 month period. The records of juveniles (*N* = 320) had the highest frequency in the first and third 4 month periods (34% and 39%, respectively). The records of the life-history stages in Region 2 are dependent on 4 month periods (X^2 = 411, *P* < 0.0001).

Neonate and YOY records are less frequent in Region 1 than in Region 2 over the years (Figure 6b,d). From the total records of each life-history stage including both regions, Region 1 had the highest frequency of YOYs in 2016 (*N* = 82, 9.9%), and neonates did not reach 2% of records in any year (Figure 6b). The records are frequent in years, with highest sampling effort in Region 2 (*i.e.*, 1994, 2008 and 2012). From the total records of each life-history stage including both regions, neonates had the highest records in 1994 (*N* = 73, 25%) and 2012 (*N* = 102, 36.5%), YOYs in 2008 (*N* = 182, 22%) and 2012 (*N* = 343, 41%) (Figure 6d) and juveniles in 2012 (*N* = 107, 16%) and 2016 (*N* = 164, 24%).

3.5 | Nursery area for *S. lewini*

Region 2 could be considered as a nursery area for scalloped hammerhead because neonates and YOYs are common and tend to remain for several months (Figure 6c) and use the region repeatedly over years (Figure 6d). Neonates and YOYs are seasonally common in catches from Frontera port to Isla Aguada port between isobaths 10–30 m, with multiple fishing areas identified by fishers off San Pedro and Frontera ports, where the highest river discharge occurs (Figure 5b).

4 | DISCUSSION

A nursery area for scalloped hammerhead was found in the terrigenous region (Region 2) of western Yucatan Peninsula, characterized by relatively shallow and turbid waters. Neonates and YOYs were commonly found over the years in May–August. The fishery-dependent data from small-scale fisheries and fishers' ecological knowledge were useful to describe the spatial and temporal distribution of life-history stages. The enforcement of management measures is necessary because the nursery is located in a region with intense fishing effort.

4.1 | Nursery area of *S. lewini* in the terrigenous region

Due to the variability in the use of coastal habitats by early life-history stages of shark species (Yates *et al*., 2012) and because sampling data to characterize nursery habitats with adequate temporal and spatial coverage are rare (Froeschke *et al*., 2010a), the present study used fishery dependent-data and fishers' ecological knowledge to describe the distribution of the early stages of the scalloped hammerhead. The spatial and temporal records of neonates and YOYs indicated that the terrigenous region characterized by shallow and turbid waters met the criteria by Heupel *et al*. (2007) to be considered as a nursery area. In this region, neonates and YOYs are common and tend to remain for several months and use the region repeatedly over years.

In general, it has been established that slow-growing shark species, such as the scalloped hammerhead, use low-risk and protected nurseries (Heithaus, 2007). The use of these turbid coastal waters is considered an antipredator strategy (Chin *et al*., 2016; Heithaus, 2004; Speed *et al*., 2010) that may also supply abundant prey resources (Heithaus, 2004; Speed *et al*., 2010); nonetheless, these need to be studied. Bonfil (1997) recorded neonates of *S. lewini*, *Sphyrna mokarran* and *Rhizoprionodon terraenovae* in the adjacent waters of Terminos Lagoon. In the present study, neonates of *R. terraenovae* were recorded in the same area, and neonates of *S. mokarran* were recorded far from shore in reef areas and near the edge of the continental shelf. Future studies should investigate food availability, consumption rate and growth rates of neonates and YOYs of scalloped hammerhead in the nursery and potential competition with other shark species that may also be using this area as a nursery.

Juveniles are the most common life-history stage in the calcareous region (Region 1). This region experiences increased water clarity due to increased filtration and lower organic matter (Ayala-Castañares & Gutiérrez-Estrada, 1990; Lara-Domínguez *et al*., 1990). Thus, it is probable that neonates and YOYs are not using this habitat because it does not provide protection from potential predators. Also, it is hypothesized that neonates and YOYs may move from the terrigenous region to the calcareous region as they grow.

Neonates and YOYs of scalloped hammerheads are absent from Terminos Lagoon. Since the 1990s neonates of only *Carcharhinus acronotus*, *Carcharhinus limbatus* and *Carcharhinus leucas* have been documented inside the lagoon (Bonfil, 1997). Fishery-independent surveys have been carried out in the lagoon without a single record of a scalloped hammerhead (Amador-del Ángel *et al*., 2012; Ayala-Pérez *et al*., 2003). Adams and Paperno (2007) indicated that coastal lagoons do not have optimal conditions for young scalloped hammerheads due to the high variability of environmental parameters. It has been documented that scalloped hammerheads prefer areas with temperature 26–30°C and salinity 28–36 ppt (Adams & Paperno, 2007; Castro, 1993), whereas Terminos Lagoon has a salinity of 12 ppt in the rainy season and 30 ppt in the dry season and a temperature of 20°C in the north cold front season and 30°C in the rainy season (Ramos-Miranda & Villalobos-Zapata, 2015; Yáñez-Arancibia & Day, 1982). Salinity regimes and temperature are attributes that dictate habitat requirements for coastal sharks (Froeschke *et al*., 2010b), and probably the salinity regime is the most important factor that explains the absence of scalloped hammerhead and other shark species inside the lagoon. Yates *et al*. (2015) found that the abundance of early stages of *S. lewini* decreased with decreasing turbidity and that this trend is altered at low salinities (*c*. 31 ppt).

Neonates and YOYs were commonly found from mid-spring to mid-summer (May–August). The seasonal records of neonates can be explained by the reproductive cycle of the scalloped hammerhead, with parturition in May and June (Branstetter, 1981). Harry *et al*. (2011) have determined that the birth season does not change between studied regions and can be partially seasonal, with neonates occurring throughout the year, but with abundant peaks during spring and summer. This has also been recorded in several studies for scalloped hammerheads in other areas (Adams & Paperno, 2007; Duncan & Holland, 2006; Harry *et al*., 2011).

4.2 | The fishery-dependent data and fishers' ecological knowledge

The fishery-dependent data over time showed catch records of all life-history stages of scalloped hammerheads, with a high frequency of neonates and YOYs (N = 1109, 59%). Fishery-dependent data provide records to test for interannual use, residency and abundance as suggested by Heupel *et al*. (2007) to identify nursery areas, and fishers' ecological knowledge provide the approximate distribution of the life-history stages in the study area. Fishers' ecological knowledge was a relevant additional source of information that complemented fishery-dependent data. It has long been recognized that fishers' knowledge of local areas can improve habitat use studies (Bergmann *et al*., 2004). Although fishers' knowledge is less considered, this information has been shown to be precise and useful for fishery management, providing valuable information on the diversity of fishes, catches, habitat preferences, stock structure, interannual variability of stock abundances, aggregations and spawning locations, local abundance trends and local extinctions (Bergmann *et al*., 2004; Serra-Pereira *et al*., 2014; Silvano & Begossi, 2012).

The present study demonstrated that fishery-dependent data and fishers' ecological knowledge provide information to support the identification of nursery areas in regions where fishing fleets operate with multiple fishing gears in multiple fishing areas (sampling effort covering a large area). Although fishers use gillnets with a variety of mesh-sizes in the calcareous region in both coastal and offshore areas, there were fewer records of neonates and YOYs in comparison to the terrigenous region, where fishers use longlines as the main fishing gear. This suggests that although there may be an effect in records of early stages due to differences in the fishing gears used between regions, the differences in the number of records are also due to a greater abundance of early stages in the terrigenous region. Potential differences in the records of life-history stages may also occur between sampling periods. Fishers acknowledge that for around 15 years they have searched for new fishing areas, with a tendency to move further away from the coast.

4.3 | Nursery area, fisheries, and oil production in the southern Gulf of Mexico

Anthropogenic impacts may negatively influence coastal nursery habitats. Most shark nurseries in waters of the Mexican Gulf are also important fishing grounds for local communities. There is a close relationship between catches of small sharks and finfish fisheries in coastal waters, because of the non-specificity of the fishing gears used (Castillo-Géniz *et al*., 1998). The proximity between nearshore waters and humans results in three major anthropogenic threats that can affect these areas: (a) habitat degradation due to coastline development, (b) pollution *via* terrestrial runoff and (c) exploitation through fisheries (Knip *et al*., 2010). In the studied area, habitat degradation and pollution are of concern due to hydrocarbons released by the oil and gas industries.

More than 80% of oil and 90% of natural gas production in Mexico occurs in the southern Gulf of Mexico (Yáñez-Arancibia *et al*., 2009). In addition, there are several small-scale fisheries in the studied area with direct or indirect impact on shark populations (Pérez-Jiménez & Méndez-Loeza, 2015). Also, shrimp trawler operations are especially concerning as they occur in areas where neonate and YOY scalloped hammerheads were recorded. Although there are no records of trawler boats catching hammerhead sharks, their operation may have indirect consequences due to habitat destruction. To combat the negative impacts by human activities, Yates *et al*. (2012) recommended that maintaining habitat diversity is essential for early stages because negative impacts on species production in one area could be buffered with increased production in other areas. Future studies should investigate the direct impact of fishing activity and the oil industry on the nursery area in the terrigenous region.

4.4 | Implications for management and conservation

The scalloped hammerhead was recently reassessed as critically endangered by the IUCN (Rigby *et al*., 2019) and is listed in CITES Appendix II (CITES, 2019). This hammerhead is one of the most common shark species in Mexican shark catches (Castillo-Géniz *et al*., 1998; Pérez-Jiménez, 2014; Pérez-Jiménez & Méndez-Loeza,- 2015); nonetheless, no specific management measures have been established. The Mexican Official Standard NOM-029-PESC-2006 (D.O.F., 2007) established temporal closed seasons in Mexican waters of the Gulf of Mexico and the Caribbean Sea for the protection of elasmobranch neonates. In the Delta of the Grijalva-Usumacinta system and Terminos Lagoon, the use of gillnets during June is prohibited. The Mexican government also established a closed season for shark fisheries from 15 May to 15 June, and 1–29 August in the states of Tabasco and Campeche (D.O.F., 2014). The appropriate enforcement of these management measures could provide protection to all life-history stages of scalloped hammerheads in the study area. This is relevant for the conservation of shark populations, because in addition to the protection of early stages, management strategies are needed for older stages to reach effective management (Kinney & Simpfendorfer, 2009).

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AUTHOR CONTRIBUTIONS

G.A.C.-G., J.C.P.-J. and I.M.-L. conceived the ideas and designed the methodology; G.A.C.-G., J.C.P.-J., I.M.-L. and J.L.C.-G. collected data; G.A.C.-G., J.C.P.-J., I.M.-L. and M.C.-F. analysed and interpreted the data; G.A.C.-G. and J.C.P.-J. wrote the manuscript; and J.C.P.-J. prepared the manuscript for submission and secured the funding to support the work.

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