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Research Article

Spatio-temporal distribution of four commercial shrimp species in the southeastern Gulf of California, Mexico

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ABSTRACT. The shrimp trawl fishery in the southeastern Gulf of California is one of the most important in Mexico due to the high economic value of the resource in the national and international market. The management of this fishery is based on permits, a no-trawling zone, a no-fishing season and regulations of fishing gears. In order to analyze the efficiency of the no-fishing season and the viability of a spatial closure, we analyzed the distribution and size structure of four species targeted by the commercial fishery during the 2005-2006 shrimp-fishing season, the white shrimp (*Penaeus vannamei*), blue shrimp (*P. stylirostris*), brown shrimp (*P. californiensis*) and crystal shrimp (*P. brevirostris*). We found that the size distribution of four shrimp species was wide and with variable frequency during the fishing season. The average biomass for each species was different throughout the fishing season, and the white and brown shrimps were the most abundant species. However, the spatial distribution of the biomass was similar for the four species. Our results suggest that the no-fishing season is more effective for brown shrimp because the individuals caught by the fishing gear have already reproduced at least once.

Keywords: shrimp, spatial-temporal distribution, abundance, management strategies, Gulf of California.

INTRODUCTION

In the southeastern Gulf of California, shrimp fishing is a sequential fishery, with juveniles captured by artisanal fishing in wetlands and coastal lagoons through so-called "*atarrayas*" (circular thrownets) or "*tapos*" (barriers placed in tidal channels to prevent the migration of shrimp to the open sea). On the other hand, adults are caught on the continental shelf by the industrial fleet using a net at each side of the trawlers (Aranceta-Garza *et al*., 2016). In particular, the industrial shrimp fishery in the Mexican Pacific is one of the most important activities in terms of economic profits, given the commercial value of the product in national and international markets and its high production volumes (García-Caudillo & Gómez-Palafox, 2005; INP, 2006), amounting to 19,155 ton per year captured in the open sea between years 2006-2013 (CONAPESCA, 2016). In the southeastern Gulf of California, the industrial shrimp fleet mainly catches four species: white shrimp (*Penaeus vannamei* Boone, 1931), blue shrimp (*P. stylirostris* Stimpson, 1874), brown shrimp (*P. californiensis* Holmes, 1900), and crystal shrimp *(P. brevirostris* Kingsley, 1878) (Aragon-Noriega, 2000). In this area, the state of Sinaloa is the main shrimp producer at the national level, with the port of Mazatlan as its main landing site.

Since its inception in 1940, the fishery operated under an open-access scheme, leading to an over-capitalized fishery currently exploited to the maximum sustainable level (DOF, 2012). The management instruments of this fishery include regulations on mesh size, a temporary closure (March to September) aimed to protect the reproductive season, a permanent fishery exclusion zone (0 to 9.14 m depth) for the protection of juveniles, and the use of turtle and fish excluder devices (TEDS) to minimize incidental bycatch (NOM-059SE MARNAT-2010). Also, in an attempt to restrain and

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reduce the fishing effort, a fishing permit scheme was adopted in 1994, and since 2000 the federal government implemented a voluntary retirement program for larger vessels that offers around US$54,000 in exchange for a fishing permit. Although spatial closure is an explicit element in the shrimp fishery management plan, its relevance in the southeastern Gulf of California has not been assessed.

In the southeastern Gulf of California, shrimp populations are segregated across the water column; white and blue shrimp are associated with shallow strata (<10 m), while brown and crystal shrimp are found in deeper down the water column (50-150 m). Annual evaluations are performed during the shrimp closed season to monitor the size structure and determine the timing of peak spawning in shrimp populations. This information is one of the cornerstones to establish the fishing season opening date. In this sense, the characterization of the size structure and spatio-temporal distribution of shrimp resources is necessary to define the structure of populations. This data makes it possible to ascertain whether the closure period established for the four shrimp species is equally suitable for all alike. In this context, the objective of this study was to investigate temporary differences in the size structure of white, blue, brown and crystal shrimp, as well as spatio-temporal variation of their biomass related to the commercial volume caught in the 2005-2006 fishing season. In addition, the spatial distribution of catches concerning the likely implementation of a spatial closure is also discussed.

MATERIALS AND METHODS

Study area

The southeastern Gulf of California is influenced mainly by westerly winds formed in the Pacific Ocean and, to a lesser extent, by trade winds, which originate in the Atlantic Ocean (Sánchez-Santillan & De la Lanza-Espino, 1994; Fig. 1).

Winds from the north and northwest prevail in winter and spring, which drive the surface flow, mainly to the southeast. The continental shelf in this area is wide, with moderate-to-severe slopes where silty-clayey sediments are the primary substrate type. Three nutrient-rich surface water masses are evident in this zone: 1) California Current, which is cold and low-salinity, flowing southward parallel to the coast of Baja California, 2) Tropical Pacific water that is warm and of intermediate salinity, flowing to the southeast heading to the Gulf of California mouth, and 3) Gulf of California water, which is warm and of higher salinity (Lavin & Marinone, 2003).

The study area comprises several water bodies, including coastal lagoons and mangrove wetlands that are important nursing grounds and protected areas for shrimp juveniles. Likewise, seven rivers flow into this region transporting nutrients that increase biological productivity and create estuarine complexes relevant as shrimp nursing grounds.

Input data

The metric and biological information of the four shrimp species was obtained from sampling events carried out in the 137 commercial fishing trips aboard shrimp trawlers. Sampling campaigns took place over the 2005-2006 shrimp fishing season, spanning from September to March. Trawlings were carried out during the day and night with the aid of semi-Portuguese shrimp nets built of polyamide (PA) thread of 1.22 mm in diameter in the body and 1.90 mm in the cod end. The upper net headline is 27.4 m, with an 8.2 cm mesh size in the body and 5.1 cm in the cod end. The otter board measured 2.74 m long by 1.12 m wide. This net is commonly used by the commercial trawl fleet in the southeastern Gulf of California (Nieto-Navarro *et al*., 2013). The average trawling time was 4 h at 7-67 m depth. One 12-17.6 kg sample of the total catch was collected onboard and was extrapolated to the total commercial catch. Individual shrimp were sorted according to species according to the species identification keys of Fisher *et al*. (1995). Also, we measured total length and total weight; also, the sex ratio was determined in the sample, and the sexual maturity status of female organisms was identified from gross examination (King, 1948; Leal-Gaxiola *et al*., 2001).

Information analysis

The frequency distribution of body length was determined for all species each month at 5 mm intervals. The relative abundance (biomass of each species) was estimated for each commercial fishing set, then quadrants measuring 3×3 nautical miles (nm) were drawn to calculate average biomass considering the number of fishing sets and biomass in each quadrant. In addition, for each month in the fishing season, and according to the information available for each species, we calculated the average biomass and its error, the latter as the division of the standard deviation by the square root of the number of sets (*n*). Relative abundance was estimated by the swept area method (Sparre & Venema, 1992), according to the following equation:

$$B_{Sp} = \frac{(W_{sp} \times C_T)/C_m}{A}$$

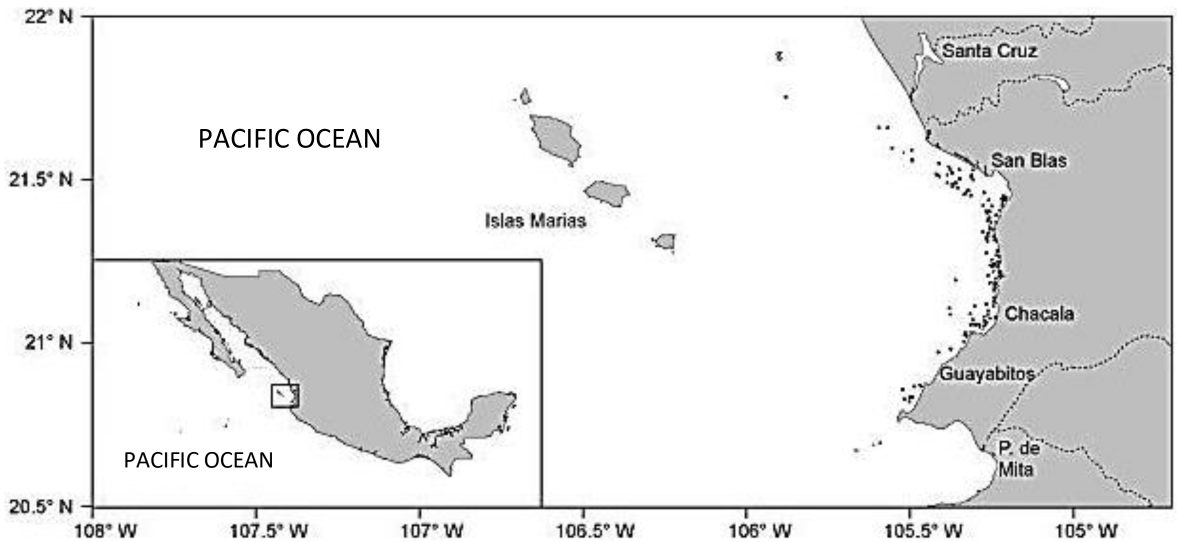

Figure 1. Southeastern Gulf of California, Mexico. The principal rivers flowing into the continental shelf are shown (dotted lines). Dots mark the location of commercial shrimp trawls analyzed in this study.

where B_{Sp} is biomass (kg m^{-2}) by trawl, W_{sp} is the weight of each species in the sample, C_T is the weight of total catch in the haul, C_m is sample weight in the haul, and A is area swept in the haul, estimated as:

$$A = D \times rs \times X2$$

where D is the distance traveled during the haul, rs is headline length, and $X2$ is the net opening coefficient (0.6 according to Klima, 1976). For the calculation of D, *a* GPS recorded the starting position, path and final position for each haul.

Differences in sex ratio between species were explored with a χ^2 test. Temporal and spatial differences in the biomass of each species were assessed through a Kruskal-Wallis test. Also, a Wilcoxon paired comparison test was performed to identify significant differences between sizes and average biomass between species.

RESULTS

A total area of 20.6 km^2 was swept, collecting 2,335 individuals, 52% of which were white shrimp (*Penaeus vannamei*), 34% brown shrimp (*P. californiensis*), 12% crystal shrimp (*P. brevirostris*), and 2% blue shrimp (*P. stylirostris*). Throughout the fishing season, most organisms of all species were females, and most of them were reproductively immature (Table 1). In the case of white, brown and crystal shrimp, the F:M sex ratio differed χ^2 = 255.4, χ^2 = 51.4, χ^2 = 23.8 respectively; $P < 0.05$), but not in the blue shrimp (Table 1).

The length of individuals captured during the fishing season showed a wide range and variable frequency for the four shrimp species (Fig. 2). The white shrimp size ranged from 60 to 230 mm in total length (TL), with the highest abundances in the 90-95 and 165-170 mm size classes. The brown shrimp showed a similar size range, with the highest abundance in the 130-135 mm size class.

The crystal shrimp showed a size range between 82 and 175 mm (TL), with the highest abundances in the 100-105 mm size class. Blue shrimp sizes were very homogenous, spanning between 117 and 232 mm (TL).

Throughout the fishing season, differences in average biomass were observed across the four species, with a higher variability at the start of the fishing season (Kruskal-Wallis χ^2 = 122.9; $P < 0.05$; Fig. 3). Throughout the fishing season, white and brown shrimp were the most abundant species, while crystal and blue shrimp had relatively minor catches. Average biomass values of white and brown shrimp were higher in September and October, subsequently decreasing in November and remaining at low levels for the rest of the season. In contrast, the biomass of blue and crystal shrimp remained relatively low throughout the whole season.

Although the most abundant species in the study area were white and brown shrimp, no significant differences were evident in the spatial distribution of biomass of the four species, suggesting a similar distribution (Kruskal-Wallis, χ^2 = 136; P = 0.484) (Fig. 4). The comparison of sizes of individuals captured *versus* the size at first maturity reported suggests that

Table 1. The number of individuals, sex ratio (female:male) and maturity stage of four shrimp species. G1: immature, G2: early maturity, G3: advanced maturity. *Statistically significant ($P < 0.05$).

Species	n	Sex ratio H:M	Maturity stage (%)		
			G1	G2	G3
Penaeus vannamei	1252	2.6:1*	78	17	5
Penaeus californiensis	763	1.7:1*	78	19	3
Penaeus brevirostris	274	1:1.5*	87	12	1
Penaeus stylirostris	46	1:1.4	81	19	

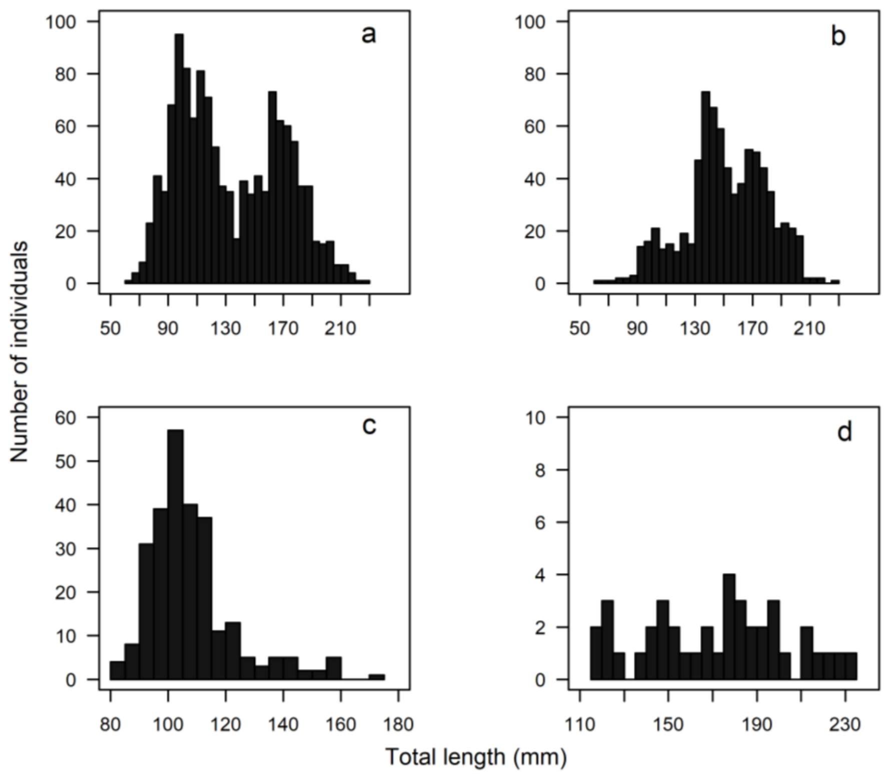

Figure 2. Size structure of commercial shrimp species during the 2005-2006 fishing season in the southeastern Gulf of California. a) *P. vannamei*, b) *P. californiensis*, c) *P. brevirostris*, and d) *P. stylirostris.*

the individuals captured were mainly white shrimp juveniles/pre-adults (Fig. 5a). In contrast, for brown shrimp the size of individuals caught exceeded the size at first maturity for most of the fishing season (Fig. 5b). The supplementary material summarizes the parameters used for calculating the biomass by commercial fishing set for each of the species evaluated.

DISCUSSION

Average sizes of individuals captured by shrimp trawls result from the technical measures imposed by shrimp fisheries management and the dynamics of shrimp stocks. In Mexico, the closed season in the shrimp fishery aims to protect the reproductive season, preventing overfishing of the spawning stock, hence preserving its recruitment and ultimately supporting the sustainable use of the shrimp resource (DOF, 1993). For this reason, knowledge of the efficiency in the protection of the breeding population in fishery resources management is highly relevant to tailor management strategies and attain resource sustainability, particularly in the establishment of closure seasons (Chen *et al.*, 2007).

The information obtained for brown and white shrimp throughout the fishing season allowed contrasting the abundance and size distribution in these species *versus* the closed season imposed in the southeastern

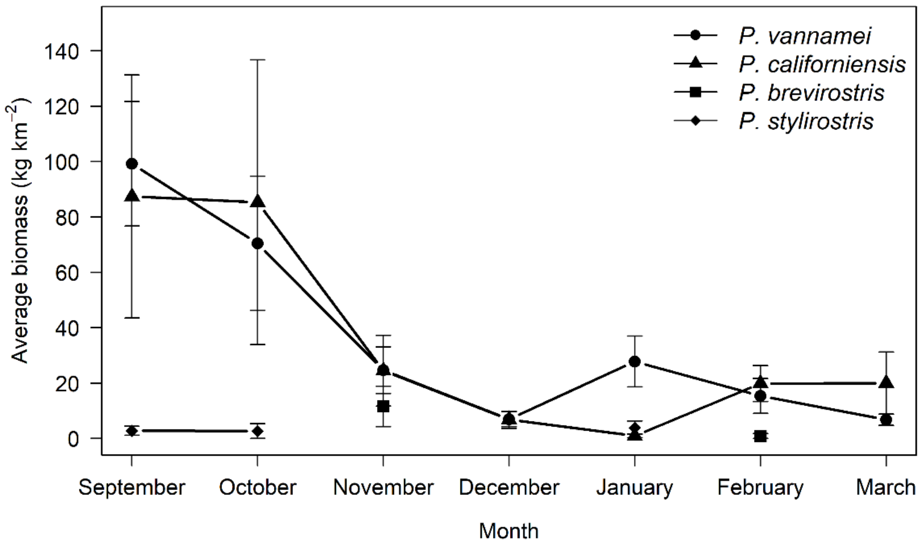

Figure 3. Average biomass of *P. vannamei, P californiensis, P. brevirostris* and *P. stylirostris* during the 2005-2006 shrimp fishing season.

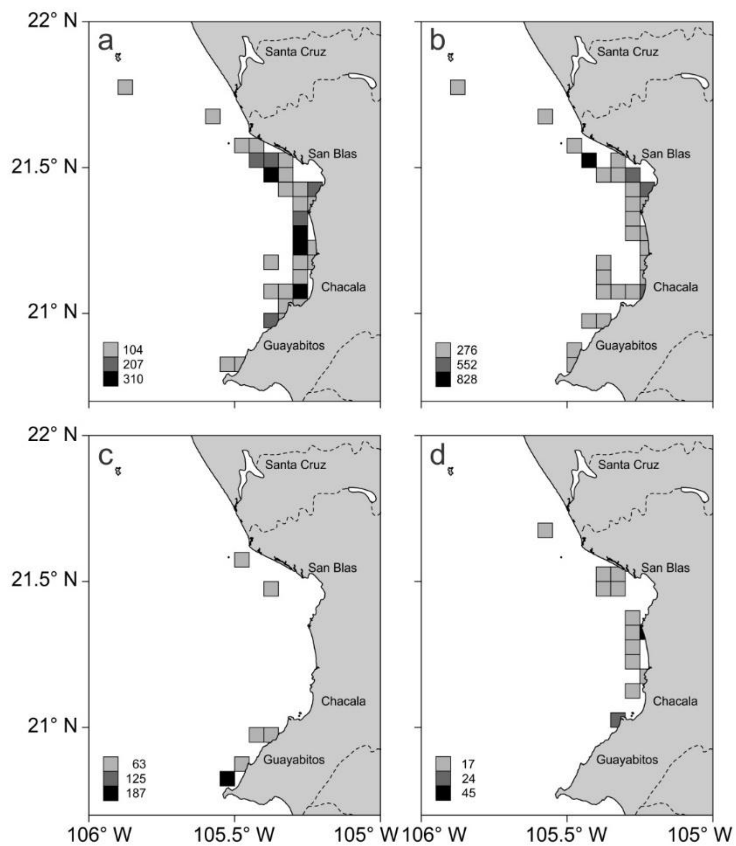

Figure 4. Spatial distribution of biomass of four commercial shrimp species during the 2005-2006 fishing season in the southeastern Gulf of California. a) *P. vannamei,* b) *P. californiensis,* c) *P. brevirostris,* and d) *P. stylirostris*. Biomass values are expressed in kg m^{-2}.

Gulf of California. In the case of the white shrimp, most of the organisms caught were slightly under the size at first maturity (LM = 192 mm) (Ramos-Cruz, 2012). In contrast, most of the brown shrimp organisms caught exceeded the size at first maturity (LM = 145 mm) (Romero-Sedana *et al*., 2004) throughout the fishing season, except for November and December.

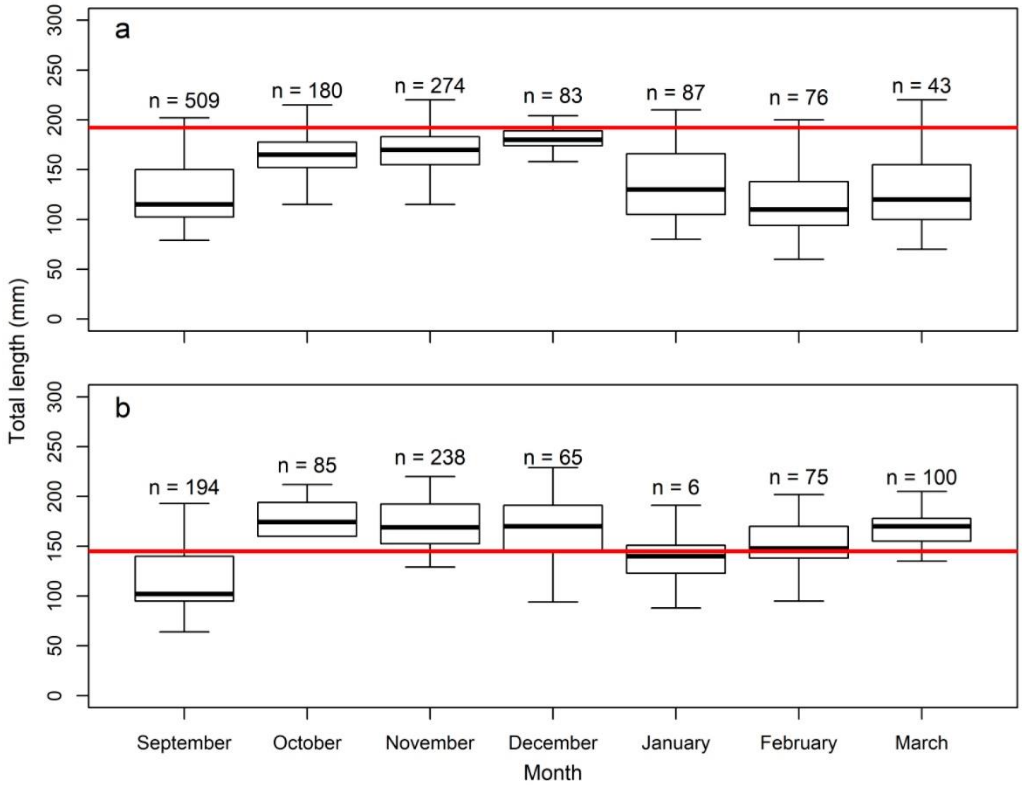

Figure 5. a) Temporal size distribution of individuals of white shrimp, and b) brown shrimp during the 2005-2006 fishing season. The horizontal red line represents the size at first maturity for white shrimp (Ramos-Cruz, 2012) and brown shrimp (Romero-Sedana *et al.,* 2004), respectively.

When the sizes caught were contrasted with the resource management measures regarding the protection of reproductive organisms, it is clear that the temporary closure works appropriately in the case of the brown shrimp, and is slightly less efficient for the white shrimp. During the fishing season, most brown shrimp individuals caught have reached the size at first maturity, and therefore have reproduced at least once before being captured. In addition, in the case of brown shrimp in the Agiabampo coastal lagoon, Sonora, two reproductive periods have been reported, one during the summer (June-July) and another during the fall (October-November) (Romero-Sedana *et al*., 2004), which suggests that reproductive individuals are captured during the fishing season, although these do not make the bulk of the catch. In the case of the white shrimp on the continental shelf of Sinaloa, a reproductive season spanning from March to October has been reported, with peaks in June and July (Garduño-Argueta & Calderón-Pérez, 1994). The lower effectiveness of the temporary closure of the white shrimp does not appear to have a significant effect on the harvestable stock, as this species shows a short life cycle with multiple recruitment periods throughout the year (Lluch-Belda *et al*., 1991). Also, for these two species, most of the females captured were immature organisms (Table 1).

It has been reported that the brown shrimp is most abundant in fishing areas between Sinaloa and northern Nayarit (Ruiz-Luna *et al*., 2010) and that the white and blue shrimp are unevenly distributed across the Gulf of California (Aragón-Noriega & Calderón-Aguilera, 2000; Aragón-Noriega *et al*., 2012). However, the results of this study suggest that the four commercial shrimp species are distributed in the southeastern Gulf of California, with brown and white shrimp making the most substantial proportion of catches. These two species showed a similar size distribution throughout the fishing season in this region. Other studies have also reported that catches in the coastal fringe of the southeastern Mexican Pacific consist primarily of brown and white shrimp (Ramos-Cruz, 2005). In contrast, catches in the upper Gulf of California have reported a higher proportion of blue shrimp (Enciso-Enciso *et al*., 2014). This difference is due to the presence of deltas, estuaries or lagoons with sandy-muddy sediments rich in organic matter in the upper Gulf of California (Galindo-Bect *et al*., 2000). In the southeastern Gulf of California, there are coastal lagoons, mangrove swamps, and rivers used by shrimp as nursing and feeding grounds. Brown and crystal shrimp depend to a lesser extent on these water bodies, but these habitats are highly important for rearing white and blue shrimp. Despite the differences in species abundances in this area, our results suggest a similar distribution of biomass for the four shrimp species along the southeastern Gulf of California. However, catches of crystal shrimp tend to occur more frequently in the southernmost portion of the study area. Probably, this does not mean that this species is restricted to this area, but instead that the fishing fleet concentrates efforts on species with higher commercial value (*i.e.*, white and brown shrimp) since the crystal shrimp is the species with the lowest market value.

On the other hand, the coexistence of these species could be because the species of the genus *Penaeus* are distributed at different depths after reaching sexual maturity (Magallón-Barajas & Jaquemin, 1976). A differential spatial closure, in this region, would not lead to significant differences either in the protection of breeding individuals, or shrimp catch volumes, in the southeastern Gulf of California. However, the temporary closure of specific areas in the southeast of the Gulf of California has been suggested (Foster & Arreguín-Sánchez, 2013) as a strategy to reduce the effect of trawls and protect some endangered species (Foster & Arreguín-Sánchez, 2013). In this sense, as shrimp fishing incidentally catches high volumes of multiple species, the implementation of protected areas, with a focus on highly vulnerable species, could be a proper management strategy for protecting the ecosystem.

Finally, although temporal and spatial protection measures seem to work correctly, the monitoring schemes in the coastal fringe under permanent closure should be further strengthened to reduce illegal fishing in this area by both large and small vessels. These measures would increase the protection of juveniles that are recruited into the adult population since these are highly vulnerable to hauling given their higher spatial aggregation in this area.

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