Reproduction and community structure of fish from winter catch sites from industrial shrimp bycatch from the northeast and southeast Mexican Pacific

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ABSTRACT

The shrimp fishery is one of the most important fisheries in the world, although the low selectivity from trawling nets has led to the capture of a large number of non-target species. Shrimp-bycatch species include a large number of fish and invertebrate species, of which fish species are the most abundant. The present study aims to determine the community structure as well as the average sizes at first maturity of the fish species from shrimp-bycatch caught from industrial fisheries in the Mexican Pacific from Sinaloa to Guerrero, from January to March 2015. The shrimp-bycatch fish diversity value was found to be 2.22. A total of 37 species of finfish were found, of which five were considered rare. The fish species with the highest Importance Value Index (IVI) levels were *Pseudupeneus grandisquamis*, *Paralichthys woolmani*, *Lutjanus peru* and *Diapterus peruvianus*. The average size at first maturity was calculated for all species. Of the analysed organisms, 90% were in the juvenile stage, including species with riverine and artisanal fisheries. The present study demonstrates the risk within marine populations to different non-target species due to the poor selectivity of shrimp trawls.

Subjects Biodiversity, Ecology, Marine Biology
Keywords Community structure, Length of maturity, Finfish, Shrimp bycatch

INTRODUCTION

Shrimp, which are among the most traded fishery products in the world, generate numerous important economic benefits (*FAO, 2017*), in both riverine and industrial fishery. As with other fisheries, shrimp fishery is not perfect (*Clucas, 1997*), especially industrial fishery. Recent years have seen an on-going emphasis on the impact of this activity on shrimp-bycatch fauna; the FAO considers this fishery the main source of discarded species (*Kelleher, 2004*; *Kumar & Deepthi, 2006*; *FAO, 2017*). The Gulf of California, widely considered the 'world's aquarium' because of its biological diversity (*Enríquez-Andrade et al., 2005*) and

the Mexican Pacific are the most important bodies of water for the Mexican shrimp fishery (*Arvizu-Martinez, 1987*; *Magallon-Barajas, 1987*).

Because shrimp are benthonic organisms, shrimp-bycatch includes a great diversity of fauna, including molluscs, echinoderms, crustaceans and various fishes. The most abundant species among shrimp-bycatch fauna are fishes, including more than 100 small-size fish species (*Perez-Mellado & Findley, 1985*) such as flatfishes, snappers and pufferfishes, among others (*Aguirre et al., 2008*; *Gibinkumar et al., 2012*; *Rábago-Quiroz et al., 2011*). More than 114,000 tons of discarded fish are generated per year (*Bojorquez, 1998*).

Even the term 'bycatch' has many definitions and considerations. Shrimp-bycatch comprises tons of non-target organism catch due to the poor selectivity of the trawls; these species are often discarded by fishery vessels or become destined for local consumption (*Alverson et al., 1994*). The main concern, however, is not only to search for potential uses of bycatch (*Kelleher, 2004*), but also to implement more selective trawls in order to reduce bycatch to a minimum. The poor selectivity of the trawls damages entire ecosystems and could deplete populations (*Alverson et al., 1994*), thus affecting even target species.

Tropical shrimp trawl fisheries are often small and have little or no room for bycatch, which means that bycatch is not cost-effective; this is the main reason that bycatch is discarded (*Kelleher, 2004*). At the global level, on-going trawl design innovations (*Boopendranath et al., 2013*) have led to greater protection of sea turtles and sea mammals (*Norma Oficial Mexicana, 1996*; *Morzaria-Luna et al., 2013*; *Norma Oficial Mexicana, 2013*); which, according to the Official Mexican Norm are threatened (*Norma Oficial Mexicana, 2010*). Still, less charismatic and less economically important species die either during or after trawling (*Hill & Wassenberg, 1990*; *Ramírez-Ramírez et al., 2008*). These organisms are then returned to the sea, which leads to environmental contamination (*Ramírez-Ramírez et al., 2008*).

In tropical countries each year, shrimp-bycatch corresponds to more than 90% of the catch (*Alverson et al., 1994*; *Kelleher, 2004*). Some of these organisms have greater marketing potential. Still, the various biological aspects of shrimp-bycatch fish are not well understood (*Ramos-Santiago et al., 2006*; *Herrera-Valdivia, López-Martínez & Morales-Azpeitia, 2016*). Because population studies of low-commercial-importance species are not cost-effective, bycatch studies are an excellent opportunity to examine these seldom-studied species (*Foster & Vincent, 2010*).

Shrimp-bycatch species must be evaluated not only because of their importance to their ecosystems and their potential commercial value (*Clucas, 1997*; *Pauly et al., 1998*; *Foster & Vincent, 2012*) but also because it is important to learn their size structure and reproductive status. Most shrimp-bycatch fauna are under 20 cm (the same size as tropical adult shrimp) and weigh less than 100 g (*Alverson et al., 1994*; *Foster & Arreguin-Sánchez, 2014*); this is because smaller organisms must work harder to escape, so many of them die from exhaustion in the trawl (*Liggins & Kennelly, 1996*). Most of these organisms are juveniles or sub-adults, most of which have not yet reproduced at least once (*Hilborn & Walters, 1991*). These factors all significantly affect the recruitment of future generations (*Broadhurst, 2000*).

In addition, the lack of information about the size at first maturity and the reproductive periods, as well as the minimum sizes of catches of less commercially valuable species, have all led to an absence of regulations for small fisheries (*Foster & Vincent, 2010*; *Morzaria-Luna et al., 2013*). The aim of this work is thus to determine the population structure and relative abundance of the fish species present in shrimp-bycatch from industrial shrimp fishery the northeast and southeast Mexican Pacific, as well as their spatial variability and potential risk involved in the recruitment of the species. Such information will serve as the basis for determining the actual status of marine communities and the effect of human activities in each region.

MATERIALS AND METHODS

This study is based on an analysis of bycatch obtained from an industrial shrimping vessel's trawling while operating on the Mexican continental shelf from Sinaloa to Guerrero (to this work this geographical area is considered Guerrero as the southeast from the Mexican Pacific and Sinaloa as northeast of the Mexican Pacific and the southeast from the Gulf of California). The work included the fauna obtained from seven catch sites (from 16.40722 to 24.40010 N and 99.42970 to 108.10895 W; Fig. 1). The catches were made during the second half of the fishing period, from January 26 to March 20, 2015, using a 70-foot-long (21.3-m) trawl with a 38-mm net mesh. Each trawl was submerged for two hours at approximate depths of 20 and 54 m, according to *Norma Oficial Mexicana (2013)*.

After the target species (shrimp) was separated on the vessel, a random 10-kg sample from the bycatch fauna was taken, from which all finfish species were separated and identified at the species level (*Allen & Robertson, 1994*). The Total Length (TL) of each organism was then measured, and gonadal maturity and sex were analysed using morpho-colorimetric methods (*Bucholtz, Tomkiewicz & Dalskov, 2008*; *Sánchez et al., 2013*); the sex was only determined in organisms with developed gonads.

Community structure

Total abundance and abundance per station of each species were then estimated. The Shannon-Weaver diversity index (H') was calculated at each station:

$$H' = -\sum P i \ln P i$$
$$P i = n i / N.$$

The similitude at each pair of stations and each pair of sampling months was calculated by the Morisita similitude index (I; *Morisita, 1959*), with modifications, in order to allow for interpretation of the results as a percentage of similitude among samples:

$$I = \frac{2\sum X i\, Y i}{(\lambda 1 + \lambda 2)(N1\, N2)} \times 100$$
$$\lambda 1 = \frac{\sum [X i (X i - 1)]}{N1(N1-1)}$$
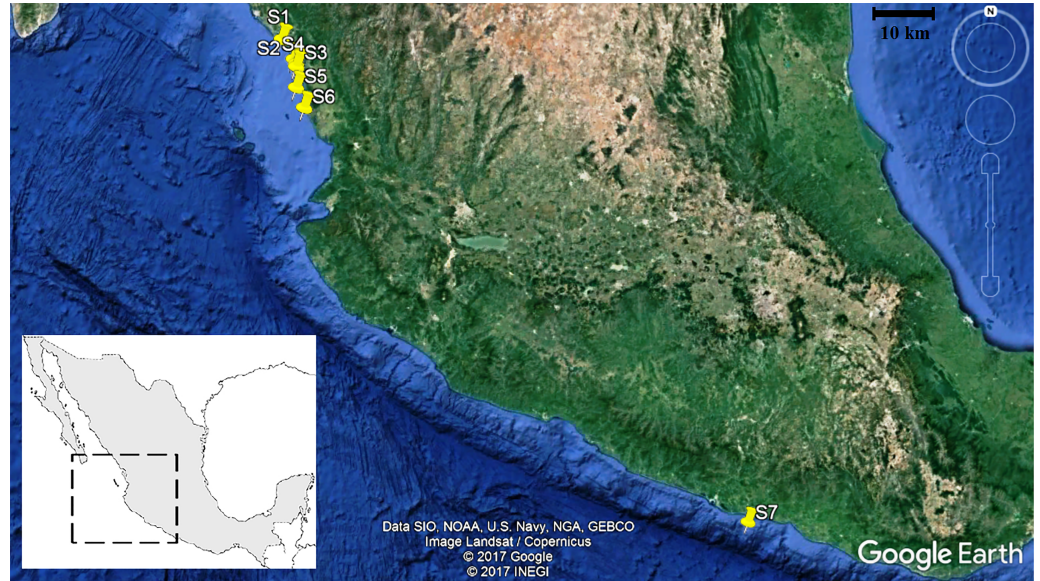$$\lambda 2 = \frac{\sum [Y i (Y i - 1)]}{N2(N2-1)}.$$

Figure 1 Location of the seven shrimp catches stations in the northeast and southeast of the Mexican Pacific. The square within the map of Mexico indicates the satellite image. Each station is indicated in yellow. Black bar represents 10 km. Map data © Google, INEGI, Data SIO, NOAA, U.S. Navu, NGA, GEBCO, Image Landsat/Copernicus.

In addition, the Relative Density (RD), Relative Frequency (RF) and Importance Value Index (IVI; *Smith & Smith, 2006*) were calculated for each species. IVI values indicated the degree of dominance of each species and their degree of constancy within the ecosystem:

$$\mathbf{RD} = \frac{\text{Total number of individuals of a species}}{\text{Total number of individuals of all species}} \times 100$$

$$\mathbf{RF} = \frac{\text{Frequency of one species}}{\text{Total frequency of all species}} \times 100$$

$$\mathbf{IVI} = \mathrm{RD} + \mathrm{FR}.$$

The 12 fish species with the highest IVI were then selected for an evaluation of the size structure per station. The sizes of the organisms were analysed to determine the normality and homoscedasticity of the sample. A one-way ANOVA at $\alpha < 0.05$ was used to find any significance among the data. Finally, the differences among stations were calculated via Tukey-Kramer multiple comparison tests with a 95% confidence level using the NCSS 2007 statistical programme.

Length at maturity (TL_m)

In order to facilitate estimation of L_m in the absence of suitable data, an empirical relationship based on linking L_m with L_∞ was used, as proposed by *Froese & Binohlan (2000)*. The resulting values were compared with the size structure among the sampled stations:

$$\log L_\infty = 0.044 + 0.9841 * \log(TL_{\max}).$$

$$\mathbf{TL_m} = 0.8979 * \log(L_\infty) - 0.0782.$$

$TL_{\max}$ was then obtained for each species in the sample from FishBase.org.

Table 1 Species richness, Shannon-Weaver diversity and Morisita similitude from shrimp-bycatch species from the northeast and southeast Mexican Pacific. (A) Species richness and Shannon-Weaver diversity at each station. (B) Morisita similitude index from each peer of stations. (C) Morisita similitude index from each peer of sampled months. J, January; F, February; M, March.

A)

	Station							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**Global**
Species Richness (S)	16	15	15	13	16	16	17	37
Diversity (H′)	1.947	2.024	2.118	1.568	2.085	2.236	1.581	2.218

B)

Station	Station						
	1	**2**	**3**	**4**	**5**	**6**	**7**
1		75.37	62.07	65.75	53.91	69.49	93.37
2	75.37		57.38	96.78	49.70	56.59	55.66
3	62.07	57.38		47.46	54.14	79.52	60.98
4	65.75	96.78	47.46		41.29	39.24	47.81
5	53.91	49.70	54.14	41.29		80.32	44.33
6	69.49	56.59	79.52	39.24	80.32		62.80
7	93.37	55.66	60.98	47.81	44.33	62.80	

C)

Month	Month		
	J	**F**	**M**
J		83.25	76.35
F	85.25		75.22
M	76.35	75.22	

RESULTS

Community structure

All fish species analysed in this study belong to the superclass Osteichthyes. The specific richness (S) was found to be among 13 and 17 species (Table 1). The total abundance of the study was 1,414 fish from 37 species, belonging to 28 families and 35 genera. The global Shannon-Weaver diversity value was found to be 2.22, with the highest diversity at station 3 (2.118). The stations' similitudes were among 39% and 93%, with the highest similitude among stations 1 and 7, which were the most geographically distant stations. Otherwise, the month similitudes were among 75% and 83%.

To this research, species with one individual (i.e., it only appeared in one station) were considered rare; these species corresponded to 16% of fish species (Table 2). The rare species were *Bagre pinnimaculatus*, *Bairdiella ronchus*, *Brotula clarkae*, *Ancylopsetta dendrítica* and *Sphyraena guachancho*. Only 13 species had an IVI of greater than 50.

Table 2 Fishes IVI from shrimp bycatch from the northeast and southeast Mexican Pacific.

Family	Specie	Freq	RD	RF	IVI	TL_{max} (cm)	TL_m (cm)
Mullidae	*Pseudupeneus grandisquamis*	HF	28.15	100	128.15	30	18.5
Paralichthyidae	*Paralichthys woolmani*	HF	22.63	100	122.63	80	44
Lutjanidae	*Lutjanus peru*	HF	15.06	100	115.06	95	51.2
Gerreidae	*Diapterus peruvianus*	HF	8.91	100	108.91	30	18.5
Tetraodontidae	*Sphoeroides pachygaster*	HF	5.16	85.71	90.87	40.5 SL	24.1 SL
Haemulidae	*Pomadasys panamensis*	HF	4.81	85.71	90.52	39	23.3
Carangidae	*Chloroscombrus orqueta*	HF	1.13	85.7	86.83	30	18.5
Synodontidae	*Synodus sцituliceps*	F	2.26	71.42	73.68	42	24.9
Triglidae	*Prionotus horrens*	F	0.85	71.42	72.27	35	21.2
Fistulariidae	*Fistularia corneta*	F	0.78	71.42	72.2	106	56.3
Serranidae	*Diplectrum macropoma*	F	2.83	57.14	59.97	18	11.7
Achiridae	*Achirus mazatlanus*	F	0.28	57.14	57.42	20	12.9
Batrachoididae	*Nautopaedium porosissimum*	F	0.24	57.14	57.42	32	19.5
Ophichthidae	*Ophichthus triserialis*	F	0.28	42.85	43.13	122	63.8
Balistidae	*Balistes polylepis*	LF	0.21	42.85	43.06	76	42
Sciaenidae	*Larimus argenteus*	LF	0.21	42.85	43.06	35	21.2
Carangidae	*Selene brevoortii*	LF	0.85	28.57	29.42	38 FL	22.8 FL
Ophidiidae	*Lepophidium prorates*	LF	0.42	28.57	28.99	29.5 SL	18.2 SL
Sciaenidae	*Isopisthus remifer*	LF	0.35	28.57	28.92	36	21.7
Clupeidae	*Opisthonema libertate*	LF	0.28	28.57	28.85	30	18.5
Carangidae	*Caranx otrynter*	LF	0.21	28.57	28.78	60	34.1
Bothidae	*Bothus constellatus*	LF	0.14	28.57	28.71	15.7	10.4
Cynoglossidae	*Symphurus prolatinaris*	LF	0.14	28.57	28.71	16.1 SL	10.6 SL
Carangidae	*Trachinotus kennedyi*	LF	0.14	28.57	28.71	90	48.8
Tetraodontidae	*Sphoeroides testudineus*	LF	1.27	14.28	15.55	38.8	23.2
Polynemidae	*Polydactylus opercularis*	LF	0.92	14.28	15.2	50	29
Scorpaenidae	*Scorpaena sonorae*	LF	0.42	14.28	14.7	15.8 SL	10.5 SL
Tetraodontidae	*Sphoeroides annulatus*	LF	0.21	14.28	14.49	44	25.9
Chaetodontidae	*Chaetodon humeralis*	LF	0.21	14.28	14.49	25.4	15.9
Engraulidae	*Anchoa walkeri*	LF	0.21	14.28	14.49	14.5	9.7
Gobiidae	*Bollmannia stigmatura*	LF	0.14	14.28	14.42	14 SL	9.4
Haemulidae	*Xenichthys xanti*	LF	0.14	14.28	14.42	24	15.2
Ariidae	*Bagre pinnimaculatus*	R	0.07	14.28	14.35	95	51.2
Sciaenidae	*Bairdiella armata*	R	0.07	14.28	14.35	30	18.5
Bythitidae	*Brotula clarkae*	R	0.07	14.28	14.35	115	60.6
Paralichthyidae	*Ancylopsetta dendritica*	R	0.07	14.28	14.35	35	21.2
Sphyraenidae	*Sphyraena guachancho*	R	0.07	14.28	14.35	200	98

Notes.
RD, Relative Density; RF, Relative Frequency; IVI, Importance Value Index; from highest to lowest IVI; Freq, Frequency; R, Rare; LF, Low frequent; F, Frequent; HF, High Frequent; TL_{max}, Maximum length (FishBase.org); TL_m, Length of maturity; SL, Standard length; FL, Fork length.

The most frequent species were the bigscale goatfish, *Pseudupeneus grandisquamis*; speckled flounder, *Paralichthys woolmani*; Pacific red snapper, *Lutjanus peru*; and the Peruvian mojarra, *Diapterus peruvianus* (Table 3); these four species presented the greatest abundances of the study, with 398, 327, 213 and 126 individuals, respectively.

Table 3 Abundance per station of fish species with highest IVI.

Species	S1	S2	S3	S4	S5	S6	S7
C. orqueta	1	2	1	3	6		3
D. peruvianus	13	9	3	15	49	26	11
D. macropoma	8	6			3	23	
F. corneta	1	5		2	2		1
L. peru	21	61	11	91	8	7	14
P. woolmani	24	24	44	22	36	74	96
P. panamensis	7	9	3	2	13	34	
P. horrens	1	6	2	1			2
P. grandisquamis	67	31	19	36	12	36	197
S. pachygaster	6	5	36	6		17	3
S. scituliceps	2	2			6	17	5

From the 12 fish species with higher IVI, only *P. grandisquamis* (IVI = 128.15), *P. woolmani* (IVI = 122.63), *L. peru* (IVI = 115.06) and *D. peruvianus* (IVI = 108.91) were present at all stations (Table 3), with maximum abundances per station of 197, 96, 91 and 49 individuals, respectively. The remainder of the species were absent from at least one station, with an average abundance of among two and 10 individuals per station.

No significant differences were found in the TL size structure in the majority of species according to latitudinal distribution; only *Synodus scituliceps* showed highly significant differences ($p < 0.01$), which were found in station 1 relative to station 2 (Fig. 2). The average sizes from *D. peruvianus*, *L. peru*, *P. woolmani* and *P. grandisquamis* were 12 cm (± 2.77 cm), 12.71 cm (± 2.81 cm), 11.51 cm (± 3.17 cm) and 12.11 cm (± 2.17 cm), respectively.

Fish sex proportion and sexual maturity

The TL_m for the species with the highest IVI values were 18.5 cm for both *P. grandisquamis* and *D. peruvianus*, 44 cm for *P. woolmani* and 51.2 cm for *L. peru* (Table 2; Fig. 2). For all analysed species, fewer than 10% of fish presented developed gonads (Fig. 3); only the species *Scorpaena sonorae* presented 100% mature individuals (although individuals from this species were only found at station 6). The absence of developed gonads did not allow for sex determination from 23 of the 37 fish species analysed. From the remaining 14 species, 90% of the organisms were found to be female, and males were found in only three species: *Diplectrum macropoma*, *D. peruvianus* and *Larimus argenteus*. In this last species, the proportion of males (75%) was higher than females (Fig. 4).

DISCUSSION

The shrimp-bycatch in Mexico, as in other tropical countries, is composed of a wide diversity of molluscs, echinoderms, crustaceans and fish species (*Herrera-Valdivia, López-Martínez & Castillo-Vargasmachuca, 2015*), which are located principally in the nation's coastal areas (*Lucano-Ramírez et al., 2001*). The present study is the first to analyse the sizes at first maturity of the fish species present in shrimp-bycatch (using both inferring
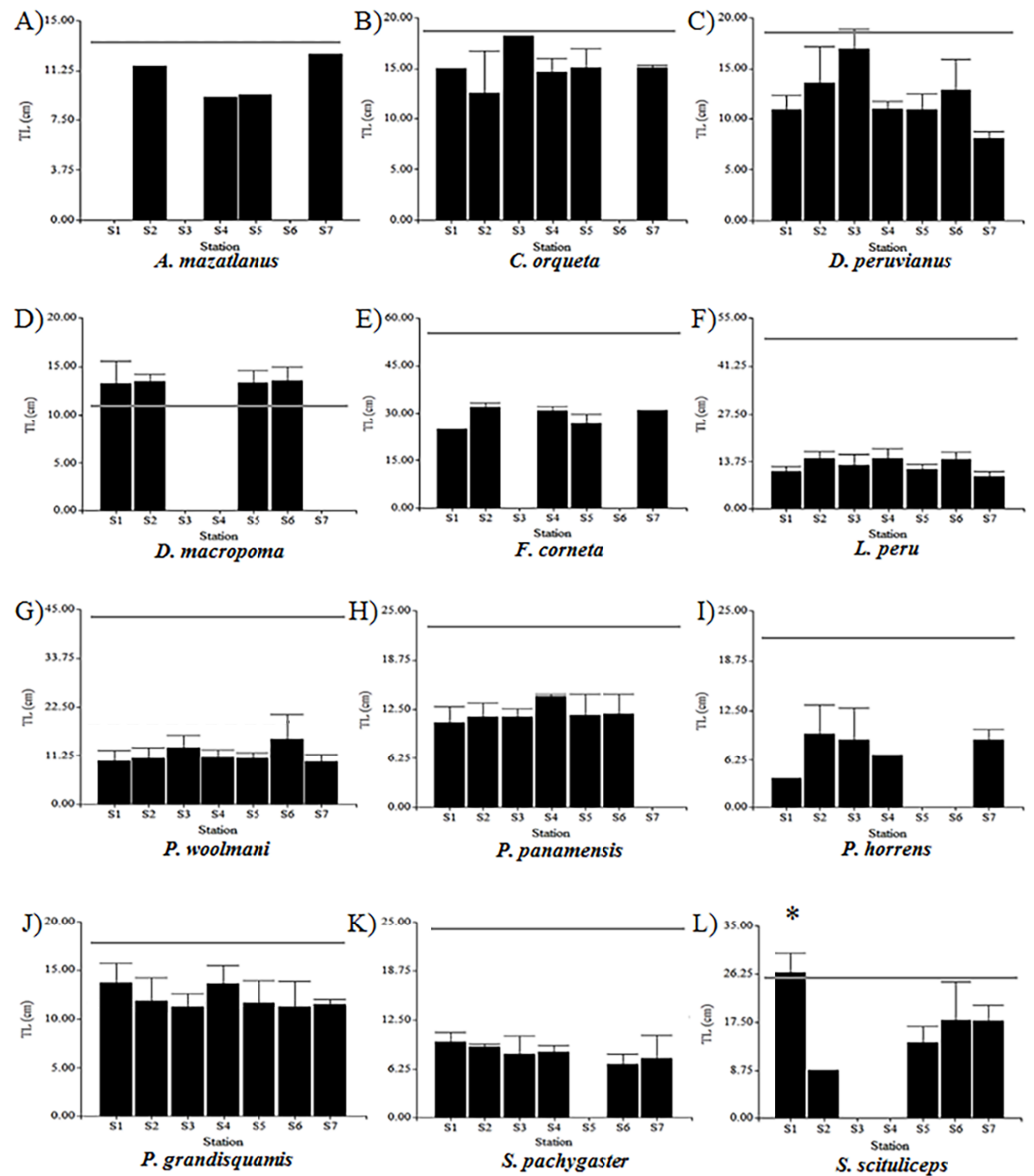
Figure 2 Fishes size structure at each sampling station. (A) *A. mazatlanus*. (B) *C. orqueta*. (C) *D. peruvianus*. (D) *D. macropoma*. (E) *F. corneta*. (F) *L. peru*. (G) *P. woolmani*. (H) *P. panamensis*. (I) *P. horrens*. (J) *P. grandisquamis*. (K) *S. pachygaster*. (L) *S. scituliceps*. The bars represent the average total length ± standard deviation. The gray line indicates the calculated length of maturity. *Represents significant differences in total length from each species among different sampled stations ($p < 0.01$).

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and direct methods) as well as community structure. The diversity values from this work correspond to other works from the Gulf of California and other subtropical areas (*Barreto, Polo & Mancilla, 2001*; *Mora, Jurado & Mendívez, 2010*; *Herrera-Valdivia, López-Martínez & Castillo-Vargasmachuca, 2015*). The diversity index helps to estimate the health of an ecosystem (*Jennings & Reynolds, 2000*). It is important to note that the diversity found
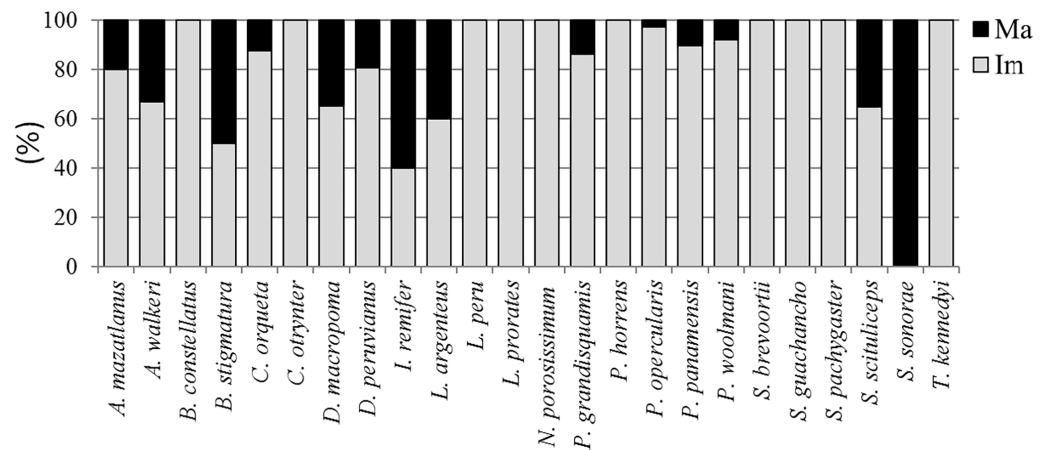
Figure 3 **Juvenile and mature fish's proportion.** Ma, mature (developed gonad); Im, immature (undeveloped gonad). Bars represent 100% of organisms. Gray bar, percentage of immature individuals; Black bar, percentage of mature individuals.
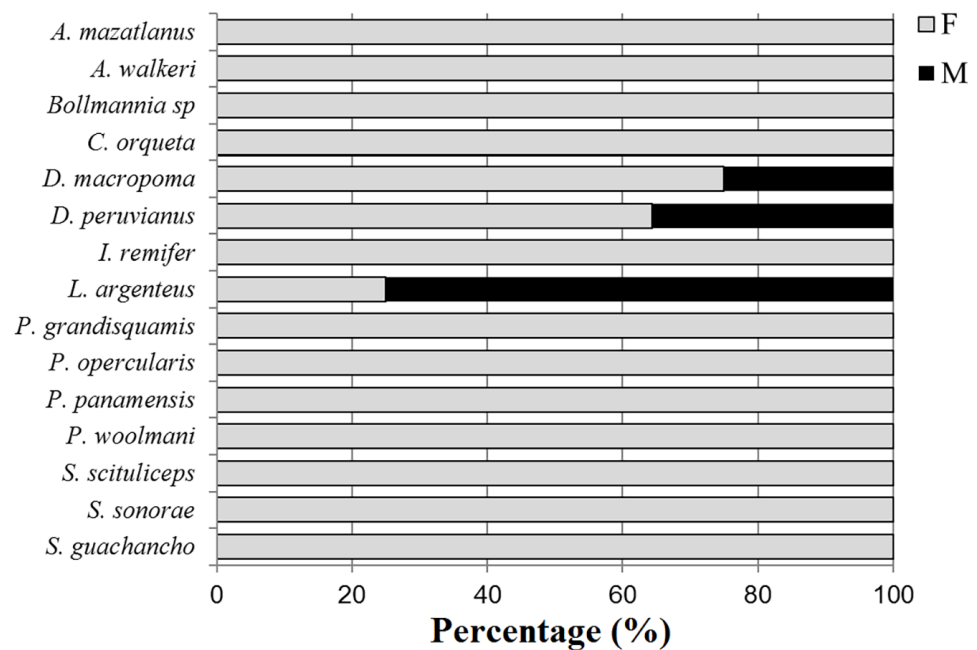
Figure 4 **Sex proportion of fishes from shrimp bycatch.** F, female; M, male. Bars represent 100% of organisms. Gray bar, percentage of females; Black bar, percentage of males.

in this study only corresponds to a subsample of shrimp-bycatch fauna, all of which are discarded as waste.

Although any variation in the trophic chain (i.e., the interrelations among prey-predator species) could play a primary role in the distribution and abundance of each species, these kinds of studies are scarce due to the generally low level of interest in less charismatic species.

Shrimping vessels do not consider variables such as temperature, dissolved oxygen, salinity and substrate, among others, and it does not seem feasible to establish these variables for better management strategies (*Foster & Arreguin-Sánchez, 2014*). This situation is mostly due to differences in the biometrics, behaviour, physiology and life history of each species (*Loverich, 1995*; *Clucas, 1997*; *Eayrs, 2007*). Most importantly, no single management/measurement solution fits all species (*Foster & Arreguin-Sánchez, 2014*).

In this study, the species richness, the similitude among stations and the size structure were not significantly found to be affected by the latitude or the month of sampling. As proof of this finding, the stations with the highest similitude were stations 1 and 7, which suggests a minimum effect of temperature on these variables. Temperature-related changes in distribution and abundance could be seen in northerly latitudes, where greater changes in temperature are generally found (*Foster & Arreguin-Sánchez, 2014*). Previous reports have established the sea bottom as one of the major determinants of the abundance of each species (*Torres & Vargas, 2007*; *Nieto-Navarro et al., 2013*). The species of fish found within shrimp-bycatch are typical of the sandy substrates of lagoon-estuarine systems where shrimp fishing is usually carried out (*Rábago-Quiroz et al., 2011*), with the exception of species associated with rocky and coral environments, such as *Chaetodon humeralis* and *Balistes polylepis*, both of which are considered low frequent.

The most representative families found in this study—Sciaenidae, Tetraodontidae, Haemulidae and Paralichthyidae, among others—are typical catches from tropical regions (*Gibinkumar et al., 2012*). Only 38% of these species were considered abundant and frequent, this suggests that most species were caught during the hauling or lifting of the nets, which also led to the low similitude among some of the sampled stations. The great majority of analysed species corresponded to benthopelagic species (*Caranx otrynter*, *Chloroscombrus orqueta*, *S. pachygaster* and *Isopisthus remifer*) and pelagic-neritic species (*Fistularia corneta*, *L. argenteus* and *Opisthonema libertate*), which coincides with the findings of previous reports from the Gulf of California and the Mexican Pacific (*López-Martínez et al., 2010*; *Nieto-Navarro et al., 2013*; *González-Sansón et al., 2014*).

The dominant species of the study—those with an IVI greater than 50—contributed more than 92% of the total abundance, which is typical of catches from the Gulf of California, Mexican Pacific and east Pacific (*Allen & Robertson, 1994*; *González-Sansón et al., 2014*; *Rábago-Quiroz et al., 2011*). Some studies have even reported that bycatch may be of greater volumes than those of the target fisheries (*Barreto, Polo & Mancilla, 2001*; *Gibinkumar et al., 2012*). The analysed organisms from previous studies have presented a large variety of size classes; most have been found to be juvenile organisms (*Alverson et al., 1994*; *Liggins & Kennelly, 1996*). A few authors have reported that shrimp-bycatch from the Gulf of California and the Mexican Pacific includes more than 100 small-size fish species (*Perez-Mellado & Findley, 1985*; *Allen & Robertson, 1994*; *Alverson et al., 1994*). For most fish species, no reports have been conducted to date on many of their biological aspects; such studies have only been conducted on the species *A. mazatlanus*, *L. peru*, *P. woolmani* and *P. grandisquamis* (*Amezcua-Linares & Castillo-Rodriguez, 1992*; *Ramos-Santiago et al., 2006*; *Herrera-Valdivia, López-Martínez & Morales-Azpeitia, 2016*; *FishBase, 2017*).

From the above discussion, we can see that it is necessary to seek strategies for the management and use of these species, since the vast majority of species have potential for commercialisation, and several of these species even have their own fisheries (*FAO, 2017*). One of the three fisheries indicators is the percentage of mature fish in a catch, which is an especially useful value for assessing eventual risks in fish stocks (*Froese, 2004*). In the literature, information on sexual maturity comes in various categories, including concepts (*Froese & Pauly, 2000*), symbols and definitions (*Ragonese & Bianchini, 2014*), all of which are closely related. The mean length at which fish of a given population become sexually mature for the first time (L_m) is an important management parameter that is used to monitor whether a sufficient number of juveniles in an exploited stock can mature and spawn (*Beverton & Holt, 1959*; *Ault, Bohnsack & Meester, 1998*; *Jennings, Reynolds & Mills, 1998*).

For teleosts, *Froese & Binohlan (2000)* have examined the use of maximum length to predict the length at first maturity (*Foster & Vincent, 2004*) because their asymptotic length is highly correlated with maximum length. *Froese & Binohlan (2000)* also found the correlation among asymptotic length and first maturity length to be 85–91% across 265 bony fish species. For teleosts, the size at first maturity is estimated as the size at which 50% of the organisms have reached sexual maturity, the size at which ovaries appear (*Kanou & Kohno, 2001*), the size of the smallest recorded female with hydrated eggs (*Nguyen & Do, 1996*), the size of the smallest recorded first breeding, and the minimum size of a recorded female to release her eggs (*Froese, 2004*).

In this regard, it is important to emphasise that both first-maturity sizes and reproductive periods are not static but are subject to environmental variations and various analytical methods (*Rodríguez-Domínguez et al., 2015*). Even overfishing plays a leading role in population reductions by increasing food availability and growth rates, both of which may affect the size at first maturity (*Froese & Binohlan, 2000*). Furthermore, in adverse environmental conditions, some species tend to undergo gonadal resorption (*Babin, 1987*; *Thomé et al., 2009*), which is why the sex proportion and the size at first maturity are often underestimated. The present study analysed the sizes at first maturity of fish species present in shrimp-bycatch, of which more than 90% were found to be outside the limits of sustainable fisheries, that is, well below the size of first maturity.

Although some species have well-established fisheries, such as *L. peru* and *P. woolmani*, such species have no official regulations for minimum catch sizes; a minimum catch size has only been proposed for *L. peru*, at 31 cm TL (*Ramos-Cruz, 2001*; *COFEMER, 2017*). *Foster & Vincent (2010)* reported among several fish species from the Gulf of California an increase in reproductive activity from winter to spring, with possible peaks in summer, which coincides with the seasonal closing of the shrimp fishery. But the excessive capturing of juveniles in the spring will have a negative effect on that summer's reproductive period and could result in more rapid depletion of small fish populations. Differences in sex proportion also indicate asynchronous maturation periods. The above evidence all demonstrates the problem of using generalised management strategies.

The National Commission of Aquaculture and Fisheries (Comision Nacional de Acuacultura y Pesca: CONAPESCA) is the Mexican governmental institution responsible

for monitoring all shrimp vessels, both industrial and riverine, and enforces compliance. However, the primary problem is that trawling is conducted in shallow waters near the coast (*Kelleher, 2004*; *Nieto-Navarro et al., 2013*), which is where most species' spawning and nesting areas are located (*Lucano-Ramírez et al., 2001*). On the other hand, since 2013 all Mexican shrimp vessels must have a fish excluder in their nets (*Norma Oficial Mexicana, 2013*); however, the abundance of fish species in shrimp-bycatch is still alarming. None of the analysed species in the current study, however, indicated a 'hazard' status or were threatened according to various conservation standards (*Norma Oficial Mexicana, 2010*; *COFEMER, 2017*; *CONABIO, 2017*), which may have been due to the scarcity of population and reproductive studies.

The inferring size at first maturity works as a first approach for creating management regulations until the specific data for each species becomes available (*Froese & Binohlan, 2000*). This study shows that many of the species present in shrimp-bycatch are at imminent risk because of their small sizes at catch and the large percentage of immature organisms within the catches; this situation not only affects the populations themselves but also causes damage to the whole trophic chain.

CONCLUSIONS

The shrimp fishing industry is one of the most important global industries. This study, using data from northeast and southeast Mexican Pacific, the shrimp fishery found an impact on a total of 37 fish species, with an average of 15 species per sampled station, which negatively affects marine diversity. Diversity from fish species from shrimp-bycatch was found to be medium-low. There were no significant differences in specific richness and abundance of individuals among latitude and sampling month.

The dominant species were *P. grandisquamis*, *P. woolmani*, *L. peru* and *D. peruvianus*, with an IVI greater than 100 and a TL_m of 18.5, 43.9, 51.2, and 18.5 cm, respectively. The shrimp fishery was found to have a negative impact on reproduction of at least 12 fish species. Of the analysed fish, only 10% had developed gonads, of which 93% were found to be female. This work highlights the potential impact of the shrimp fishery on fish population dynamics and the need to improve the selectivity of shrimp trawls, and the imminent risk that marine communities face.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Jorge de Jesus Tirado-Ibarra performed the experiments, analyzed the data, authored or reviewed drafts of the paper, approved the final draft.
- Mariany Loya-Rodriguez and Jose Carlos Morales-Arevalo performed the experiments, authored or reviewed drafts of the paper, approved the final draft.
- Isabel Rosario Muñoz-Garcia conceived and designed the experiments, authored or reviewed drafts of the paper, approved the final draft, sampling and identification.
- Francisco Martinez-Perez performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft.
- Jorge Saul Ramirez-Perez conceived and designed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Laura Rebeca Jimenez-Gutierrez conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.

Data Availability

The following information was supplied regarding data availability:

Jimenez-Gutierrez, Rebeca (2018): Data S1. figshare. https://doi.org/10.6084/m9. figshare.5731185.v1.

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REFERENCES

Aguirre H, Amezcua F, Madrid-Vera J, Soto C. 2008. Length–weight relationship for 21 fish species from a coastal lagoon in the southwestern Gulf of California. *Journal of Applied Ichthyology* **24(1)**:91–92 DOI 10.1111/j.1439-0426.2007.01043.x.

Allen GR, Robertson DR. 1994. *Fishes of the tropical Eastern Pacific.* Honolulu: University of Hawai press, 355.

Alverson DL, Freeberg MH, Pope JG, Murawski SA. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper No. 339. Rome, Food and Agriculture Organization of the United Nations, 233. *Available at http://www.fao.org/docrep/003/T4890E/T4890E00.HTM* .

Amezcua-Linares F, Castillo-Rodriguez ZG. 1992. Alimentación y reproducción del sol *Achirus mazatlanus* (Steindachner, 1869) en el sistema lagunar costero de Agua Brava, Pacífico de México. *Anales Del Centro de Ciencias Del Mar Y Limnologia, Universidad Nacional Autónoma de México* **19**:181–194.

Arvizu-Martinez J. 1987. Fisheries activities in the Gulf of California, Mexico. CalCOFI Report XXVIII, 32–36. *Available at http://www.inapesca.gob.mx/portal/documentos/publicaciones/pelagicos/Arvizu-Martinez_1987.pdf* .

Ault JS, Bohnsack JA, Meester GA. 1998. A retrospective (1979–1996) multispecies assessment of coral reef fish stocks in the Florida keys. *Fishery Bulletin* **96**:395–414.

Babin PJ. 1987. Apolipoproteins and the association of egg yolk proteins with plasma high density lipoproteins after ovulation and follicular atresia in the rainbow trout (*Salmo gairdneri*). *Journal of Biological Chemistry* **262(9)**:4290–4296.

Barreto CG, Polo G, Mancilla B. 2001. Análisis biológico pesquero y económico de la fauna acompañante en la pesquería de arrastre industrial colombiana. Tropical shrimp fisheries and their impact on living resources. Fisheries Circular No. 974. Rome, Food and Agriculture Organization of the United Nations, 234–270. *Available at http://www.fao.org/docrep/007/y2859e/y2859e09.htm*.

Beverton RJH, Holt SJ. 1959. A review of the lifespans and mortality rates of fish in nature, and their relation to growth and other physiological characteristics. In: Wolstenholme GEW, O'Connor M, eds. *The lifespan of animals. CIBA foundation colloquia on ageing*. Vol. 5. London: J. and A. Churchill LTD., 142–180.

Bojorquez LF. 1998. Bycatch utilization in Mexico. In: *Report and proceedings on the FAO/DFID expert consultation on bycatch utilization in tropical fisheries. Bejing, Rome*. Rome: Food and Agriculture Organization of the United Nations, 21–28.

Boopendranath MR, Pravin P, Gibinkumar TR, Sabu S, Madhu VR. 2013. Investigations on juvenile fish excluder cum shrimp sorting device (JFE-SSD). *SpringerPlus* **2**:271 DOI 10.1186/2193-1801-2-271.

Broadhurst MK. 2000. Modifications to reduce bycatch in prawn trawls: a review and framework for development. *Reviews in Fish Biology and Fisheries* **10**:27–60 DOI 10.1023/A:1008936820089.

Bucholtz RH, Tomkiewicz J, Dalskov J. 2008. Manual to determine gonadal maturity of herring (*Clupea harengus* L.). DTU Aqua-report 197-2008. National Institute of Aquatic Resources, Charlottenlund, 45.

Clucas I. 1997. A study of the options for the utilization of bycatch and discards from marine capture fisheries. FAO Fisheries Circular. No. 928. Rome, Food and Agriculture Organization of the United Nations, 59.

COFEMER. 2017. Acuerdo mediante el cual se da a conocer La actualización de la carta nacional pesquera. Secretaría de agricultura, ganadería, desarrollo rural, pesca y alimentación. *Available at http://www.cofemersimir.gob.mx/mirs/21468*.

CONABIO. 2017. *Sistema Nacional de Información Sobre Biodiversidad (SNIB-CONABIO).* México: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. *Available at https://www.gob.mx/conabio*.

Eayrs S. 2007. *A guide to bycatch reduction in tropical shrimp-trawl fisheries.* Rome: Food and Agriculture Organisation of the United Nations, 110.

Enríquez-Andrade R, Anaya-Reyna G, Barrera-Guevara JC, Carvajal-Moreno MdlA, Martínez-Delgado ME, Vaca-Rodríguez J, Valdés-Casillas C. 2005. An analysis of critical areas for biodiversity conservation in the Gulf of California region. *Ocean and Coastal Management* **48**:31–50 DOI 10.1016/j.ocecoaman.2004.11.002.

FAO, Food and Agriculture Organization of the United Nations. La pesca del camarón, a examen. Consulted julio de 2017. *Available at http://www.fao.org/news/story/es/item/10170/icode/*.

FishBase. Lutjanus peru (Nichols and Murphy, 1922). Pacific red snapper. Consulted May 2017. *Available at http://www.fishbase.org/summary/Lutjanus-peru*.

Foster SJ, Arreguin-Sánchez F. 2014. Using distribution patterns of small fishes to assess small fish by-catch in tropical shrimp trawl fisheries. *Animal Conservation* **17**:217–224.

Foster SJ, Vincent ACJ. 2004. Life history and ecology of seahorses: implications for conservation and management. *Journal of Fish Biology* **65**:1–61.

Foster SJ, Vincent ACJ. 2010. Using life-history information to assess potential effects of shrimp trawling on small fishes. *Journal of Fish Biology* **76**:2434–2454 DOI 10.1111/j.1095-8649.2010.02631.x.

Foster SJ, Vincent ACJ. 2012. Advice in spite of great uncertainty: assessing and addressing bycatch of small fishes with limited data using Stellifer illecebrosus as a case study. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22(5)**:639–651 DOI 10.1002/aqc.2243.

Froese R. 2004. Keep it simple: three indicators to deal with overfishing. *Fish and Fisheries* **5(1)**:86–91 DOI 10.1111/j.1467-2979.2004.00144.x.

Froese R, Binohlan C. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. *Journal of Fish Biology* **56(4)**:758–773 DOI 10.1111/j.1095-8649.2000.tb00870.x.

Froese R, Pauly D. 2000. *FishBase 2000: concepts designs and data sources.* Los Baños: ICLARM, 344.

Gibinkumar TR, Sabu S, Pravin P, Boopendranath MR. 2012. Bycatch characterization of shrimp trawl landings off southwest coast of India. *Fish Technology* **49**:132–140.

González-Sansón G, Aguilar-Betancourt C, Kosonoy-Aceves D, Lucano-Ramírez G, Ruiz-Ramírez S, Flores-Ortega JR, Hinojosa-Larios A, De Asís Silva-Bátiz F. 2014. Species and size composition of fishes in Barra de Navidad lagoon, Mexican central Pacific. *Revista BiologÍa Tropical* **62(1)**:129–144.

Herrera-Valdivia E, López-Martínez J, Castillo-Vargasmachuca S. 2015. Estrés en la comunidad íctica en la pesca de arrastre del camarón en el norte del Golfo de California. *Revista Biología Tropical International Journal of Tropical Biology* **63(3)**:741–754 DOI 10.15517/rbt.v63i3.14823.

Herrera-Valdivia E, López-Martínez J, Morales-Azpeitia R. 2016. New depth record of the dappled flounder *Paralichthys woolmani* (Pleuronectiformes: Paralichthyidae) in the Gulf of California, México. *Revista de Biología Marina Y Oceanografía* **51(3)**:699–701 DOI 10.4067/S0718-19572016000300022.

Hilborn R, Walters CJ. 1991. *Quantitative fisheries stock assessment: choices, dynamics and uncertainties.* New York: Chapman and Hall.

Hill BJ, Wassenberg IR. 1990. Fate of discards from prawn trawlers in Torres Straight. *Australian Journal of Marine and Freshwater Research* **41**:53–64 DOI 10.1071/MF9900053.

Jennings S, Reynolds JG. 2000. Impact fishing on diversity: from pattern to process. In: Kaiser M, De Groot SJ, eds. *Effect of fishing on non-target species and habitats.* Blackwell Science, 235–248.

Jennings S, Reynolds JD, Mills SC. 1998. Life history correlates of responses to fisheries exploitation. *Proceedings of the Royal Society B: Biological Sciences* **265**:333–339 DOI 10.1098/rspb.1998.0300.

Kanou K, Kohno H. 2001. Early life history of a seahorse, *Hippocampus mohnikei*, in Tokyo Bay, Japan. *Icthyological Research* **48**:361–368 DOI 10.1007/s10228-001-8159-9.

Kelleher K. 2004. *Discards in the world's marine fisheries: an update.* Rome: Food and Agriculture Organization of the United Nations.

Kumar AB, Deepthi GR. 2006. Trawling and by-catch: implications on marine ecosystem. *Current Science* **90(8)**:922–931.

Liggins GW, Kennelly SJ. 1996. By-catch from prawn trawling in the Clarence River estuary, New South Wales, Australia. *Fisheries Research* **25**:347–367 DOI 10.1016/0165-7836(95)00415-7.

López-Martínez J, Herrera-Valdivia E, Rodríguez-Romero J, Hernández-Vázquez S. 2010. Peces de la fauna de acompañamiento en la pesca industrial de camarón en el Golfo de California, México. *Revista Biología Tropical* **58(3)**:925–942.

Loverich GF. 1995. Thinking beyond the traditional codends. In: *Solving bycatch: considerations for today and tomorrow: proceedings of the solving bycatch workshop.* Seattle: University of Alaska Sea Grant College Program, 101–106.

Lucano-Ramírez G, Ruíz-Ramírez S, Aguilar-Palomino B, Rojo-Vázquez JA. 2001. Listado de las especies de peces de la región costera de Jalisco y Colima, México. *Ciencia Y Mar* **5(15)**:13–20.

Magallon-Barajas FJ. 1987. The Pacific shrimp fishery of Mexico. CalCOFI Report XXVIII, 43–52. *Available at http://calcofi.org/publications/calcofireports/v28/Vol_28_Magallon-Barajas.pdf*.

Mora E, Jurado V, Mendívez W. 2010. Diversidad de macroinvertebrados en la plataforma continental de Ecuador. *Revista Ciencias Del Mar Y Umnología* **4(2)**:101–116.

Morisita M. 1959. Measuring of interspecific association and similarity between communities. *Memoirs of the Faculty of Science, Kyushu University, Series A Biology* **3**:65–80.

Morzaria-Luna HN, Ainsworth CH, Kaplan IC, Levin PS, Fulton EA. 2013. Indirect effects of conservation policies on the coupled human-natural ecosystem of the upper Gulf of California. *PLOS ONE* **8(5)**:e64085 DOI 10.1371/journal.pone.0064085.

Nguyen VL, Do HH. 1996. Biological parameters of two exploited seahorse species in a Vietnamese fishery. In: *Proceedings of the 1st international conference in Marine Conservation. Hong Kong.*

Nieto-Navarro JT, Zetina-Rejón M, Arreguín-Sánchez F, Palacios-Salgado DS, Jordán F. 2013. Changes in fish bycatch during the shrimp fishing season along the eastern coast of the mouth of the Gulf of California. *Journal of Applied Ichthyology* **29(3)**:610–616 DOI 10.1111/jai.12160.

Norma Oficial Mexicana. 1996. NOM-EM-001-PESC-1996: por la que se establece el uso obligatorio de dispositivos excluidores de tortugas marinas en las redes de arrastre durante las operaciones de pesca de camarón en el Océano Pacífico, incluyendo el Golfo de California. *Available at http://www.dof.gob.mx/nota_detalle.php?codigo=4875991&fecha=18/03/1996*.

Norma Oficial Mexicana. 2010. NOM-059-SEMARNAT-2010: protección ambiental-Especies nativas de México de flora y fauna silvestres-Categorías de riesgo y especificaciones para su inclusión, exclusión o cambio-Lista de especies en riesgo. *Available at http://www.profepa.gob.mx/innovaportal/file/435/1/NOM_059_SEMARNAT_2010.pdf*.

Norma Oficial Mexicana. 2013. NOM-002-SAG/PESC-2013: para ordenar el aprovechamiento de las especies de camarón en aguas de jurisdicción federal de los Estados Unidos Mexicanos. *Available at http://www.dof.gob.mx/nota_detalle_popup.php?codigo=5306294*.

Pauly D, Dalsgaard J, Christensen V, Froese R, Torres FJ. 1998. Fishing down marine food webs. *Science* **279**:860–863 DOI 10.1126/science.279.5352.860.

Perez-Mellado JL, Findley LT. 1985. Evaluación de la ictiofauna del camarón capturado en las costas de Sonora y norte de Sinaloa, México. In: Yañez Arancibia A, ed. *Recursos Pesqueros Potenciales de México: La pesca acompañante del camarón.* Mexico City: Universidad Nacional Autonoma, 201–254.

Rábago-Quiroz CH, López-Martínez J, Valdez-Holguín JE, Nevárez-Martínez MO. 2011. Distribución latitudinal y batimétrica de las especies más abundantes y

frecuentes en la fauna acompañante del camarón del Golfo de California, México. *Revista Biología Tropical* **59(1)**:255–267.

Ragonese S, Bianchini ML. 2014. It is time to discard the Rikhter & Efanov's natural mortality-age at maturity estimator from the stock assessment scientist's toolbox? *Pan-American Journal of Aquatic Sciences* **9**:58–65.

Ramírez-Ramírez JC, Huerta S, Arias L, Prado A, Shirai K. 2008. Utilization of fisheries by catch and processing wastes for lactic acid fermented silage and evaluation of degree of protein hydrolysis and *in vitro* digestibility. *Revista Mexicana de Ingeniería Química* **7**:195–204.

Ramos-Cruz S. 2001. Evaluación de la pesquería de huachinango *Lutjanus peru* en la zona costera de Salina Cruz, Oaxaca, México, durante 1995. *INP. SAGARPA. México. Ciencia Pesquera* **15**:151–158.

Ramos-Santiago E, Ramírez-Gutiérrez JM, Mendoza-Rodríguez R, Tapia-García M. 2006. Reproducción, distribución y abundancia del pez *Pseudupeneus grandisquamis* (Perciformes: Mullidae), en el Golfo de Tehuantepec, México. *Revista Biología Tropical* **54(4)**:1103–1112.

Rodríguez-Domínguez G, Castillo-Vargasmachuca SG, Pérez-González R, Aragón-Noriega EA. 2015. The interanual variability of size at maturity of the Brown crab *Callinectes bellicosus* Stimpson, 1859 (Brachyura, Portunidae) in the Gulf of California. *Crustaceana* **88(12–14)**:1339–1350 DOI 10.1163/15685403-00003491.

Sánchez J, Perea A, Buitrón B, Romero L. 2013. Scale of gonad maturity stages of Jack mackerel *Trachurus murphyi* Nichols 1920. *Revista Peruana de Biología* **20(1)**:35–44.

Smith RL, Smith TM. 2006. *Ecología*. 6ta ed. España: Pearson Educación, 642.

Thomé RG, Santos HB, Arantes FP, Domingos FF, Bazzoli N, Rizzo E. 2009. Dual roles for autophagy during follicular atresia in fish ovary. *Autophagy* **5(1)**:117–119 DOI 10.4161/auto.5.1.7302.

Torres ER, Vargas FA. 2007. Diversidad y distribución de los crustáceos estomatópodos y decápodos en el estuario del río Gallegos (Santa Cruz, Argentina). *Revista de Biología Tropical* **55(1)**:113–119.