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# Elasmobranch bycatch by prawn trawls in the Gulf of California: First comprehensive analysis and the effect of fish escape devices

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ABSTRACT

We report results from the first detailed investigation of elasmobranch bycatch that contains data on species, sex, and length-frequency distributions of animals collected in the coastal south-eastern and entrance region of the Gulf of California. Using data from fishery-independent prawn trawl surveys between 2011–17, we found differences between years and zones in the number of species per tow in summer when more samples were taken, but we did not find differences in autumn and winter. We present size-frequency distributions with size at first maturity for *Urobatis halleri*, *Urotrygon chilensis*, *Rhinoptera steindachneri*, *Hypanus dipterurus*, *Gymnura marmorata*, and *Pseudobatos glaucostigmus*, which were the species most frequently present in the prawn trawls during the surveys. These distributions are presented by zone, depth stratum, and season (mainly summer, when commercial prawn trawling is prohibited, and thus information from commercial catches is not available). We found significant differences in the mean size between mature females and mature males for five of these six species. We also found that fish escape devices installed in the prawn nets early in 2016 improved the escape of mid-sized rays, demonstrating size selectivity of the fishery and suggesting the potential to improve further the escape of large-sized rays by modifying fish escape devices. Furthermore, the large number of rays caught (21 species) compared with the number of sharks caught (four species) suggests much lower catchabilities for sharks than for rays in demersal prawn trawl gear.

## 1. Introduction

Demersal trawl fisheries can have significant consequences for populations, food webs, and ecosystems (Crowder and Murawski, 1998). In Mexico, the industrial prawn trawl fishery has operated since 1921 in the Gulf of California (GoC) and on the southwest coast near to the border with Guatemala (Aguilar and Grande-Vidal, 2008), representing the most important fishery in terms of income and employment, and providing ~40 % of the total national fish production value (Lluch-Cota et al., 2007). The composition of retained and discarded elasmobranch catches in the industrial demersal prawn trawling fishery of Mexico has seldom been reported and never in detail. This lack of specific data limits stock assessment and ecological risk assessment of the elasmobranch species. Fishery-independent surveys in several parts of the world have shown that elasmobranch bycatch species have suffered marked declines in abundance (Walker, 2005a) and that in multi-species fisheries, non-target species require special management to prevent depletion of their populations, particularly species with low productivity such as elasmobranchs (Walker, 2005b).

In the GoC, previous work on evaluating the impacts of prawn trawling on elasmobranchs is mostly limited to lists of the main bycatch species taken during industrial fishing (López-Martínez et al., 2010; Rodríguez-Romero et al., 2012; Herrera-Valdivia et al., 2015), and the latitudinal and bathymetric distribution of the most abundant and frequent bycatch species taken during research cruises (Rábago-Quiroz et al., 2011). A few studies have analysed the somatic growth rates and population dynamics of some of the most common species (e.g., *Urobatis halleri* and *Pseudobatos productus*) (López-Martínez et al., 2010;

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Morales-Azpeitia, 2013; Soto-Barron, 2013) or their feeding habits (Navarro-González, 2012).

Detailed information on elasmobranch catch composition by species, sex, and size-frequency for separate sampling zones, seasons, depth strata, and years is thus very limited. This limitation is in contrast to the artisanal fisheries, where elasmobranch catch composition in the GoC has been studied intensely (Pérez-Jiménez et al., 2005; Bizzarro et al., 2009a, Bizzarro et al., 2009b, Bizzarro et al., 2009c, Bizzarro et al., 2009d; Smith et al., 2009; Torres-Herrera and Tovar-Ávila, 2014). In addition, earlier works have been undertaken on commercial vessels, and thus do not provide information about elasmobranchs present during the summer, which is closed to prawn fishing because the prawns reproduce in this season (NOM-002-SAG/PESC-2013-DOF, 2013).

The present study focuses on the elasmobranch species caught as bycatch during fishery-independent prawn trawling surveys undertaken during 2011–17 by the National Fisheries and Aquaculture Institute of Mexico (INAPESCA) in the coastal south-eastern and entrance region on the continental shelf of the GoC. Although the surveys occurred during all seasons, activity was most intense during summer, when prawn trawling is prohibited. We report the number of species collected, and for each of the six most commonly caught species, compare the size-frequency distributions among the zones, seasons, and depth strata surveyed.

We expected the presence of bycatch reduction devices (BRDs), such as the turtle exclusion device (TED) (mandatory in Mexico since 1996) and a fish escape device (FED) (mandatory since the start of 2016) fitted to all prawn trawl nets, to affect the size-frequency distributions of these species both in the catch and the population. Appropriate data to investigate the size-selectivity of the TED in the net were not available, but we investigated the size-selectivity of the FED by testing for a difference in the size-frequency distributions of each of the six most commonly-caught species (a taxonomically diverse set of rays) between the periods before and after adoption of the FEDs.

## 2. Material and methods

### 2.1. Data collection

The GoC, also known as the Sea of Cortés (Fig. 1a), is located on the northwest coast of Mexico, covering an area of ~350,000 km$^2$ (Ezcurra et al., 2009). Oceanographically, it is strongly influenced by north-westerly winds and two major oceanic currents from the Pacific Ocean. The two currents are the cold-temperate water south-flowing California Current during winter-spring and the warm water north-flowing Mexican Current during summer-autumn. Both currents produce noticeable variations in physical and chemical conditions, such as SST, mixing tides and upwelling (Álvarez-Borrego, 1983; Álvarez-Borrego and Lara-Lara, 1991; Lavín and Marinone, 2003; Álvarez-Borrego, 2010).

We used data from sampling undertaken onboard RV INAPESCA I and RV BIP XII, between 2011 and 2017 (Table 1). INAPESCA has assigned zone and subzone numbers to prawn fishery survey areas along the coast (Fig. 1b). For our study, we selected data from zones 30, 40, and 60 as representative of the coastal south-eastern and entrance region on the continental shelf of the GoC (Liedo-Galindo and González-Ania, 2005).

Animals were collected by sampling the catch at each of a series of fixed stations on the continental shelf at between 9 and 74 m depth, for a trawl time of 60 min at a towing speed of 2 knots, using a cone-shaped trawl net on each side of the boat. The nets were the typical design (model "super mixto", 33 m in length) (Quevedo, 2001) used in the industrial demersal prawn trawl fishery. These nets are constructed of nylon monofilament webbing with a mesh size of 51 mm in the square, belly, and wings, and 38 mm in the cod end. The horizontal trawl mouth is held open when towed, by two metal doors (3.35 × 1.68 m).

Each of the two survey trawl nets was fitted with a TED at the rear of the main body of the net immediately in front of the cod end (mandatory for Mexico's demersal prawn trawl fishery since 1996) (DOF, 2013). TEDs used in the fishery and surveys have an angled oval or semi rectangular-shaped grill, ranging in size from 810 × 1150 mm to 1070 × 1300 mm and constructed of either stainless steel bars (6–16 mm thick) or aluminum tubes (9–32 mm diameter) spaced up to 102 mm apart. The grill is designed to prevent turtles from entering the cod end and to guide them out through an escape hatch (1420 mm wide x 510 mm long) forced open on the underside of the net.

At the beginning of 2016 following a legislative change (DOF, 2013, 2016), each survey net and prawn trawl net used in the fishery was also fitted with a FED ("fish-eye" design) inside the cod end, well behind the TED, to facilitate the escape of fishes from the cod end. According to the legislation the FEDs should be attached to the top of the cod end, as most fishers do. However, some fit the FED to the underside of the cod end. The convenience of setting the device to the underside of the cod end is currently under investigation. The FED is constructed as an elliptical ring (200 mm minor axis and 400 mm major axis), attached to three bars, 630 mm long and joined at the apex to form a cone 520 mm long that supports the ring so that it provides a vertical opening in the net that faces forwards. The FED bars are 9 mm thick and mostly of stainless steel, but some fishers use other materials.

For each of the most commonly-caught elasmobranch species, a sample was randomly selected from each trawl, whereas all the specimens were sampled for less commonly-caught species. The animals were frozen on board and transported to the Regional Aquaculture and Fisheries Research Centre (CRIAP) of Bahía de Banderas from INAPESCA in Nayarit state for processing. In the laboratory, the species were identified by using several taxonomic keys (McEachran and Notarbartolo-Di Sciara, 1995; Castro-Aguirre and Espinosa Pérez, 1996; Corro-Espinosa and Ramos-Carrillo, 2004; Santana-Morales et al., 2004). All individuals were sexed and total length (TL) was measured from the tip of the snout to the flattened tip of the caudal fin for all sharks and one species of ray (*Pseudobatos glaucostigmus*). Disc width across the widest part of the disc (DW) was measured for the rest of the rays. Size at first maturity for each of the males and females of each species was determined as the size of the smallest observed mature animal among the collected animals. Maturity stages were assigned to each animal based on macroscopic inspection of the reproductive structures: primarily ovary development confirmed by uterus and oviducal condition for the females; and testis development confirmed by clasper rigidity stage for males (Walker, 2005a) (Table 2). Animals recorded as 'immature' or 'maturing' were classed as 'immature' and only those recorded as 'mature' were classed as 'mature'. Size at birth for *Urobatis halleri* and *Rhinoptera steindachneri* was determined by considering the smallest free-swimming specimen and the largest embryo (Bizzarro et al., 2007).

### 2.2. Data processing

Not every individual elasmobranch randomly selected from the catch during the INAPESCA prawn surveys had all the variables of zone, season, depth stratum, and the year recorded. Thus, provided an animal had zone recorded as 30, 40, or 60, it was included for analyses of size-frequency composition by season where the season was known, by depth stratum where the depth was known, and by period where the year was known. As observers were instructed in 2017 to focus on collecting larger individuals, rather than specimens at random, of *Hypanus dipterurus*, *Gymnura marmorata*, and *P. glaucostigmus* for separate length-at-age studies, we used only the data from trawls in 2016 for these three species. However, as sample sizes for *Urobatus halleri*, *Urotrygon chilensis*, and *R. steindachneri* were very small in 2016 and the instruction to observers did not apply to these last species, we used data from both 2016 and 2017. Thus, size-frequency composition was analysed for each of the six most frequently-caught species in the trawls using available 2011–16 data for three of the species and 2011–17 data for the other three species.

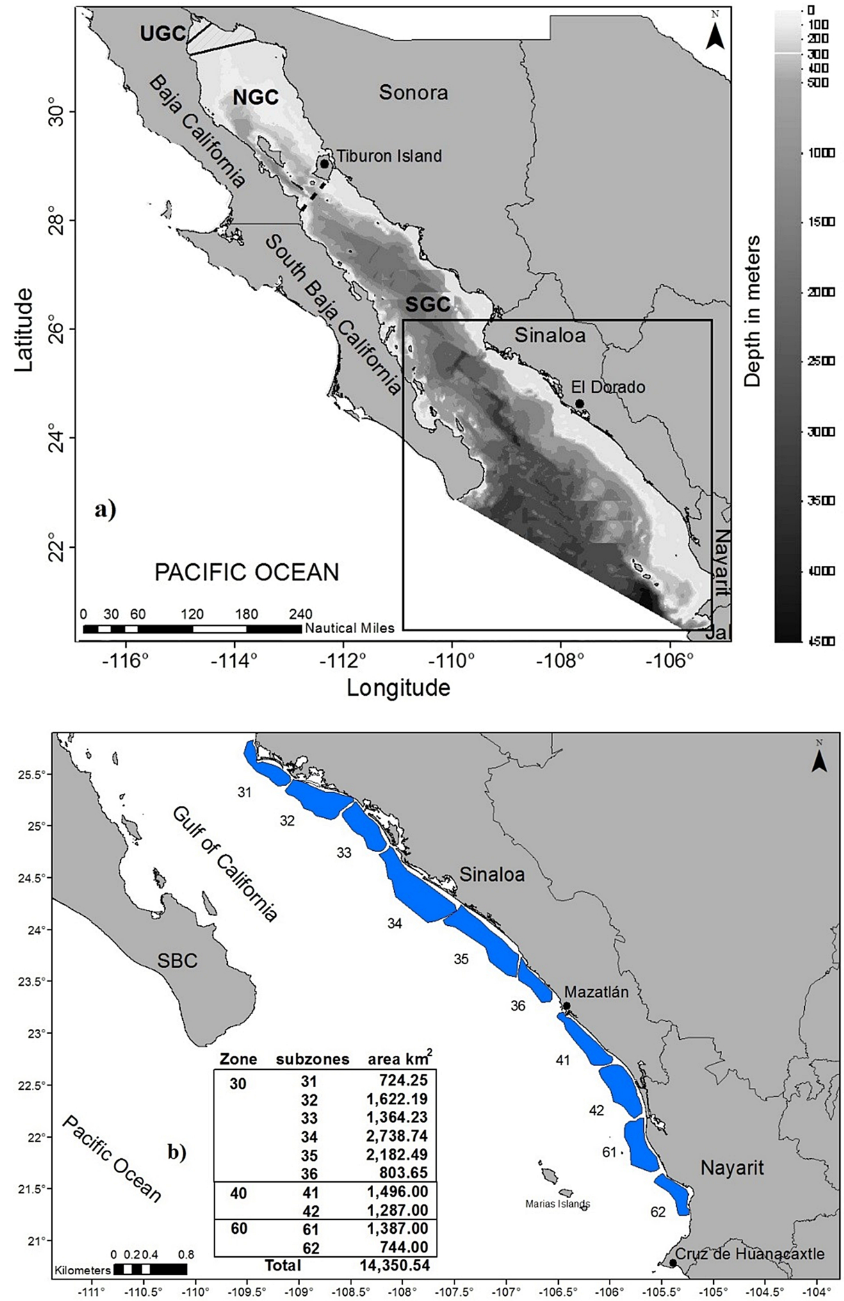


**Fig. 1.** a) Regions and bathymetry of the Gulf of California (GoC) (adapted from Lavín and Marinone, 2003), b) the subzones in the south-eastern and entrance region on the continental shelf of the GoC adopted for prawn fishery studies by INAPESCA, Mexico (adapted from Liedo-Galindo and González-Ania, 2005). UGC, NGC, SGC: Upper, Northern, and Southern Gulf of California, respectively, SBC: South Baja California.

**Table 1**
Sampling seasons by year and zone during this study.

| Year | Zone 30 | Zone 40 | Zone 60 |
|---|---|---|---|
| 2011 | Summer | Summer | Summer |
| 2012 | Summer | Summer | Summer |
| 2013 | Summer | Summer | Summer |
| 2014 | Summer, Autumn and Winter | Summer, Autumn and Winter | Summer |
| 2015 | Summer | Summer | Summer |
| 2016 | Summer, Autumn and Winter | Summer, Autumn and Winter | Summer, Autumn and Winter |
| 2017 | Spring and Summer | Spring and Summer | Spring and Summer |

**Table 2**
Maturity stages assigned based on development of reproductive structures (adapted from Walker, 2005a).

| Maturity stages | Females | | | Males | |
|---|---|---|---|---|---|
| | Ovary | Oviducal gland | Uterus | Testis | Clasper |
| Immature | Not differentiated from the epigonal organ, without visible oocytes. | Indistinct from anterior oviduct. | Indistinct from anterior oviduct. | Not differentiated from the epigonal organ. | Pliable, short with no calcification. |
| Maturing | Differentiated from the epigonal organ, with whitish oocytes of diameter $< 3$ mm. | Differentiated from anterior oviduct, larger than wider. | Uniformly enlarged tubular structure. | Differentiated from epigonal organ, not lobed or vascularized. | Enlarged, partly calcified. |
| Mature | Differentiated from the epigonal organ, with yellowish oocytes of diameter $\geq 3$ mm. | Heart shape well differentiated from oviduct. | Enlarged tubular structure distended, with eggs or embryos. | Enlarged, lobed and vascularized | Enlarged, rigid and fully calcified. |

**Table 3**
Number of animals collected and number of trawl survey tows by year, zone and season in the coastal south-eastern and entrance region of the Gulf of California.

| Year | Number of animals and species collected in brackets with number of trawl tows in parentheses | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spring | | | Summer | | | Autumn | | | Winter | | | |
| | Zone 30 | Zone 40 | Zone 60 | Zone 30 | Zone 40 | Zone 60 | Zone 30 | Zone 40 | Zone 60 | Zone 30 | Zone 40 | Zone 60 | |
| 2011 | – | – | – | [82,3](4) | [105,8](7) | [46,7](5) | – | – | – | – | – | – | **[233,9] (16)** |
| 2012 | – | – | – | [191,11](28) | [267,11](23) | [104,5](15) | – | – | – | – | – | – | **[562,17] (66)** |
| 2013 | – | – | – | [80,9](13) | [304,15](25) | [183,12](27) | – | – | – | – | – | – | **[567, 17] (65)** |
| 2014 | – | – | – | [127,10](7) | [232,14](23) | [146,14](23) | [31,6](3) | [120,11](8) | | [286,11](23) | [47,6](6) | – | **[989,17] (93)** |
| 2015 | – | – | – | [74,5](3) | [189,12](13) | [184,11](14) | – | – | – | – | – | – | **[447,14] (30)** |
| 2016 | – | – | – | [144,9](15) | [112,11](20) | [107,8](14) | [8,2](1) | [191,13](19) | [111,10](6) | [112,9](17) | [23,9](6) | [27,7](5) | **[835,18] (103)** |
| 2017 | [37,5](15) | [190,15](18) | [119,13](20) | [621,16] (36) | [36,5](9) | [138,4](15) | – | – | – | – | – | – | **[1141,19] (113)** |
| **Total** | **[37,5] (15)** | **[190,15] (18)** | **[119,13] (20)** | **[1319,21] (106)** | **[1245,17] (120)** | **[908,16] (113)** | **[39,7] (4)** | **[311,14] (27)** | **[111,10] (6)** | **[398,16] (40)** | **[70,11] (12)** | **[27,7] (5)** | **[4774,25] (486)** |

**Table 4**
Elasmobranch composition in prawn trawls in the three zones sampled in coastal south-eastern and entrance region of the Gulf of California between 2011 and 2017. P = presence of species. Species in bold font were used to analyse size-frequency distributions trawls before and after the introductions of Fish Escape Devices (FEDs).

| Order | Family | Scientific name | Common name | Zone 30 | Zone 40 | Zone 60 | Percentage of trawl tows in which each species occurred | Commercial Importance |
|---|---|---|---|---|---|---|---|---|
| Carcharhiniformes | Carcharhinidae | *Rhizoprionodon longurio* | Pacific sharpnose shark | P | P | P | 4.63 | High |
| Carcharhiniformes | Sphyrnidae | *Sphyrna lewini* | Scalloped Hammerhead shark | P | P | P | 17.56 | High |
| Carcharhiniformes | Triakidae | *Mustelus albipinnis* | White-margin fin hound shark | P | | | 0.73 | High |
| Carcharhiniformes | Triakidae | *Mustelus henlei* | Brown smoothhound shark | P | | | 1.46 | High |
| Myliobatiformes | Aetobatidae | *Aetobatus laticeps* | Pacific eagle ray | P | P | P | 6.34 | Medium |
| Myliobatiformes | Dasyatidae | ***Hypanus dipterurus*** | Diamond stingray | P | P | P | 24.39 | High |
| Myliobatiformes | Dasyatidae | *Hypanus longus* | Longtail stingray | P | P | P | 6.10 | High |
| Myliobatiformes | Gymnuridae | ***Gymnura marmorata*** | California Butterfly ray | P | P | P | 25.85 | High |
| Myliobatiformes | Mobulidae | *Mobula munkiana* | Pygmy devilray | P | | P | 0.49 | Medium |
| Myliobatiformes | Urotrygonidae | *Urobatis maculatus* | Spotted round ray | P | P | P | 8.05 | Low |
| Myliobatiformes | Urotrygonidae | ***Urobatis halleri*** | Haller's round ray | P | P | P | 35.85 | Low |
| Myliobatiformes | Urotrygonidae | *Urotrygon aspidura* | Spiny-rail round ray | P | | | 0.49 | Low |
| Myliobatiformes | Urotrygonidae | *Urotrygon nana* | Dwarf round ray | P | P | P | 10.73 | Low |
| Myliobatiformes | Urotrygonidae | *Urotrygon rogersi* | Roger's round ray | P | P | P | 12.44 | Low |
| Myliobatiformes | Urotrygonidae | ***Urotrygon chilensis*** | Chilean round ray | P | P | P | 18.29 | Low |
| Myliobatiformes | Urotrygonidae | *Urotrygon munda* | Munda round ray | P | | | 0.98 | Low |
| Rajiformes | Rajidae | *Beringraja inornata* | California skate | P | | | 0.49 | Medium |
| Rajiformes | Rajidae | *Rostroraja velezi* | Rasptail skate | P | | | 0.73 | Medium |
| Rajiformes | Rhinopteridae | ***Rhinoptera steindachneri*** | Pacific cownose ray | P | P | P | 33.90 | Medium |
| Torpediniformes | Narcinidae | *Narcine entemedor* | Cortez numfish | P | P | P | 8.54 | Low |
| Torpediniformes | Narcinidae | *Narcine vermiculata* | Vermiculate numfish | P | P | P | 13.90 | Low |
| Torpediniformes | Narcinidae | *Diplobatis ommata* | Pacific dwarf numbfish | P | | | 0.24 | Low |
| Torpediniformes | Platyrhinidae | *Platyrhinoidis triseriata* | Thornback fanray | | P | | 0.24 | Low |
| Rhinopristiformes | Rhinobatidae | ***Pseudobatos glaucostigmus*** | Speckled guitarfish | P | P | P | 35.61 | High |
| Rhinopristiformes | Trygonorrhinidae | *Zapteryx xyster* | Southern banded guitarfish | P | | | 7.56 | Medium |

**Table 5**
Summary statistics for the effects of FEDs on the size-frequency distributions of the six most common species in prawn.

| Species | Sample sizes | | Size of animals (cm) | | | Test of 2011–15 versus 2016–17 or 2016 | |
|---|---|---|---|---|---|---|---|
| | 2011–15 | 2016–17 or 2016 | Min | Max | $\chi^2$ | DOF | Significance |
| *Urobatis halleri* | 327 | 380 | 5 | 28 | 315.32 | 3 | P < 0.001 |
| *Urotrygon chilensis* | 177 | 38 | 6 | 31 | 19.442 | 3 | P < 0.05 |
| *Gymnura marmorata* | 203 | 53[A] | 21 | 92 | 26.911 | 3 | P < 0.001 |
| *Hypanus dipterurus* | 67 | 54[A] | 16 | 69 | 22.217 | 3 | P < 0.001 |
| *Rhinoptera steindachneri* | 242 | 31 | 24 | 74 | 92.903 | 3 | P < 0.001 |
| *Pseudobatos glaucostigmus* | 247 | 61[a] | 14 | 82 | 10.354 | 3 | N.S. |

[a] Samples for 2016 only post adoption of fish excluder device.

The size at first maturity for each sex of these six species is presented with length-frequency distributions by zone, season, and depth stratum (< 12 and ≥12 m). For this study, the seasons were defined as follows: spring, April–June; summer, July–September; autumn, October–December; and winter, January–March, depending on when the surveys were completed. Levene's test was performed to test for homogeneity of variances in the number of species of elasmobranchs per trawl among zones, seasons, depth strata, and years, and the Shapiro-Wilk analysis was used to test for normal distributions. Furthermore, we applied Kruskal-Wallis test, using the individual tows in each year as replicates, to test for differences in the number of species present among years, zones, seasons (for seasons, we tested summers, autumns, and winters) and depth strata. For the autumn and winter samples, we tested zones 30 and 40 in each year.

The ratio of mature females to mature males of the most frequently occurring species was analysed using a chi-squared test. Mature females and mature males were tested for normality (Anderson–Darling test) and equal variances (*F*-test for independent samples). Potential differences in mean size were then tested using either the Mann–Whitney test or the unequal variance t statistic (Welch test), as appropriate. We scored the commercial importance of 25 species as low, medium, or high based on retention rates and value in the artisanal fishery (Bizzarro et al., 2009b).

To test for the effects of FEDs on the size distributions of chondrichthyans in the catch, we compared the size-frequency distributions of the six most common species before and after FEDs were introduced into the prawn trawls nets at the start of 2016. As our results and preliminary analyses showed that there were often differences in size distributions between seasons and years, we used the overall size distributions of these species in the bycatch surveys for summer, over all the years from 2011 to 2015, as the standard to compare the 2016 or 2016–17 size distributions, depending on the species. We combined the size data of each species, ordered the sizes, and calculated the quartiles of the size distribution over the years 2011–17 for *Urobatis halleri*, *Urotrygon chilensis*, and *R. steindachneri* and 2011–16 for *H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*. The frequencies of rays in each

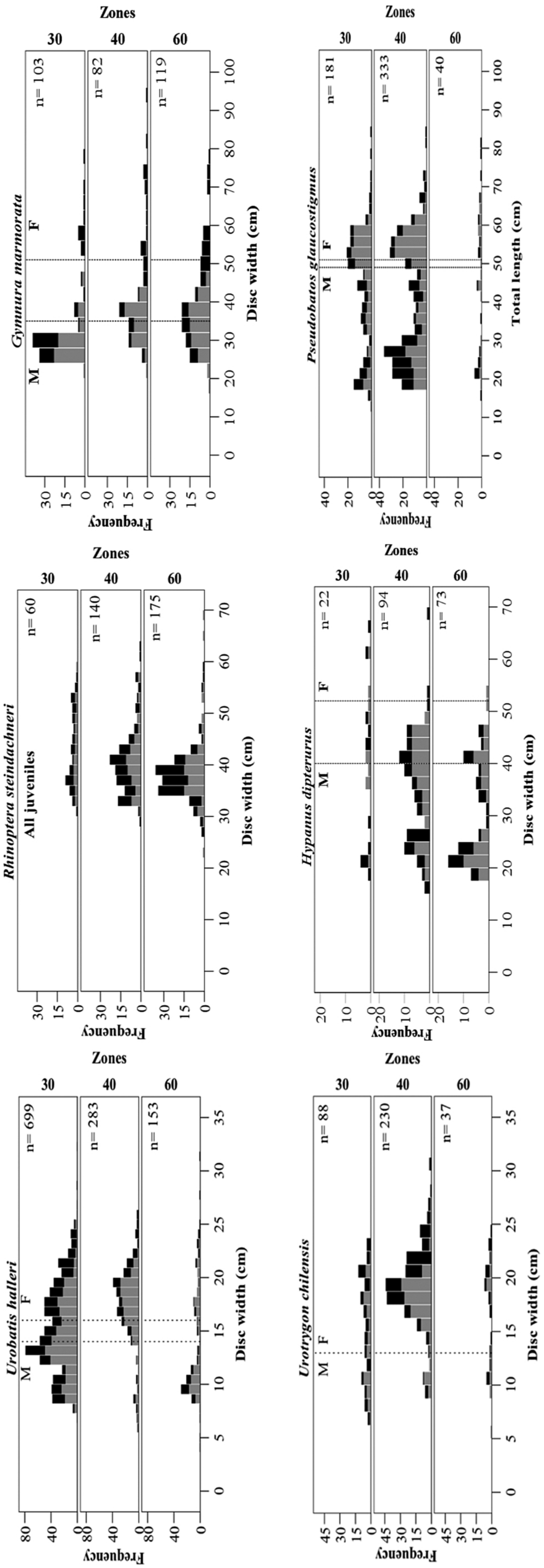


**Fig. 2.** Size-frequency distributions of the six species most commonly caught in the prawn trawls by zone (30, 40 and 60), combined over all depth strata and seasons during 2011–17 (*U. halleri*, *U. chilensis*, and *R. steindachneri*) or 2011–16 (*H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*). The females are shown as black bars and males as grey bars, and the two dashed lines represent the sizes at first maturity for the females (F) and males (M), separately.

quartile before 2016 and during 2016 or 2016–17 were then compared using a chi-square test of heterogeneity. This provided a consistent method for each species and avoided any bias in choosing size categories.

## 3. Results

### 3.1. Species composition of the catch

A total of 4774 elasmobranchs (25 species from 14 families within 5 orders) were collected and analysed during 18 surveys and 486 tows during 2011–17. The animals were collected from all three zones (30, 40, and 60), four seasons, and two depth strata. The percentage of tows with elasmobranch catches varied among the zones: 34 % in zone 30, 36 % in zone 40, and 30 % in zone 60, and among the seasons: 11 % in spring, 70 % in summer, 7% in autumn and 12 % in winter (Table 3). Of the 25 species caught by the prawn trawl, 8 were scored as of high commercial importance, 6 as of medium, and 11 as of low importance (Table 4).

Levene's test detected significant heterogeneity of variances in the number of species of elasmobranchs in summer per zone ($F_{(2,329)}$ = 3.71, $P$ = 0.02) and years ($F_{(6,325)}$ = 2.55, $P$ = 0.01). This is likely to be a result of sampling more seasons in some years and zones (Table 3). But not between the two depth strata ($F_{(1,329)}$ = 1.76, $P$ = 0.02). For spring season, Levene's test detected significant heterogeneity of variances in the number of species of elasmobranchs per zone ($F_{(2,50)}$ = 5.14, $P$ = 0.01) but not between the two depth strata ($F_{(1,51)}$ = 0.63, $P$ = 0.43). For autumn, Levene's test did not detect significant heterogeneity of variances in the number of species of elasmobranchs per zone ($F_{(1,29)}$ = 0.42, $P$ = 0.51), per year ($F_{(1,29)}$ = 0.91, $P$ = 0.34), and between the two depth strata ($F_{(1,28)}$ = 0.09, $P$ = 0.76). We also found that for winter samples, Levene's test did not detect significant heterogeneity of variances in the number of species of elasmobranchs per zone ($F_{(1,50)}$ = 0.44, $P$ = 0.50), per year ($F_{(1,50)}$ = 0.15, $P$ = 0.69), and between the two depth strata ($F_{(1,50)}$ = 0.05, $P$ = 0.82).

The number of species for each zone in each year deviated significantly from a normal distribution (W = 0.87, $P$= < 0.001). The Kruskal–Wallis test showed only significant differences in the number of species per tow among the summers from 2011 to 2017 ($W_{(6)}$ = 27.26, $P$ = < 0.001) and among zones ($W_{(2)}$ = 18.75, $P$ = < 0.001). The post hoc test showed that the differences were between years 2013–2016, 2014–2016 and 2014–2017, and zones 30–40 and 30–60, when more tows were done. For autumn, the analysis did not show differences in the number of species per tow between 2014 and 2016 ($W_{(1)}$ = 0.0004, $P$ = 0.98), among zones ($W_{(1)}$ = 1.05, $P$ = 0.30) and between the two depth strata ($W_{(1)}$ = 0.25, $P$ = 0.61). For winter, the analysis did not show differences in the number of species per tow between 2014 and 2016 ($W_{(1)}$ = 0.43, $P$ = 0.51) and between zones ($W_{(1)}$ = 0.27, $P$ = 0.59). But the test showed significant differences between the two depth strata ($W_{(1)}$ = 7.53, $P$ = 0.006). Thus, there is no evidence of any change between years and zones in the number of species present per tow for autumn and winter samples.

In zone 30, the maximum number of species of elasmobranchs was 16 in summer 2017. In zone 40, the maximum number of species was 15 in spring 2017 and summer 2013, whereas in zone 60, the maximum number of species was 14 in summer 2014. In 2014, 2016 and 2017, when samples from different seasons were available, summer was the season with the highest number of species in most cases (Table 3).

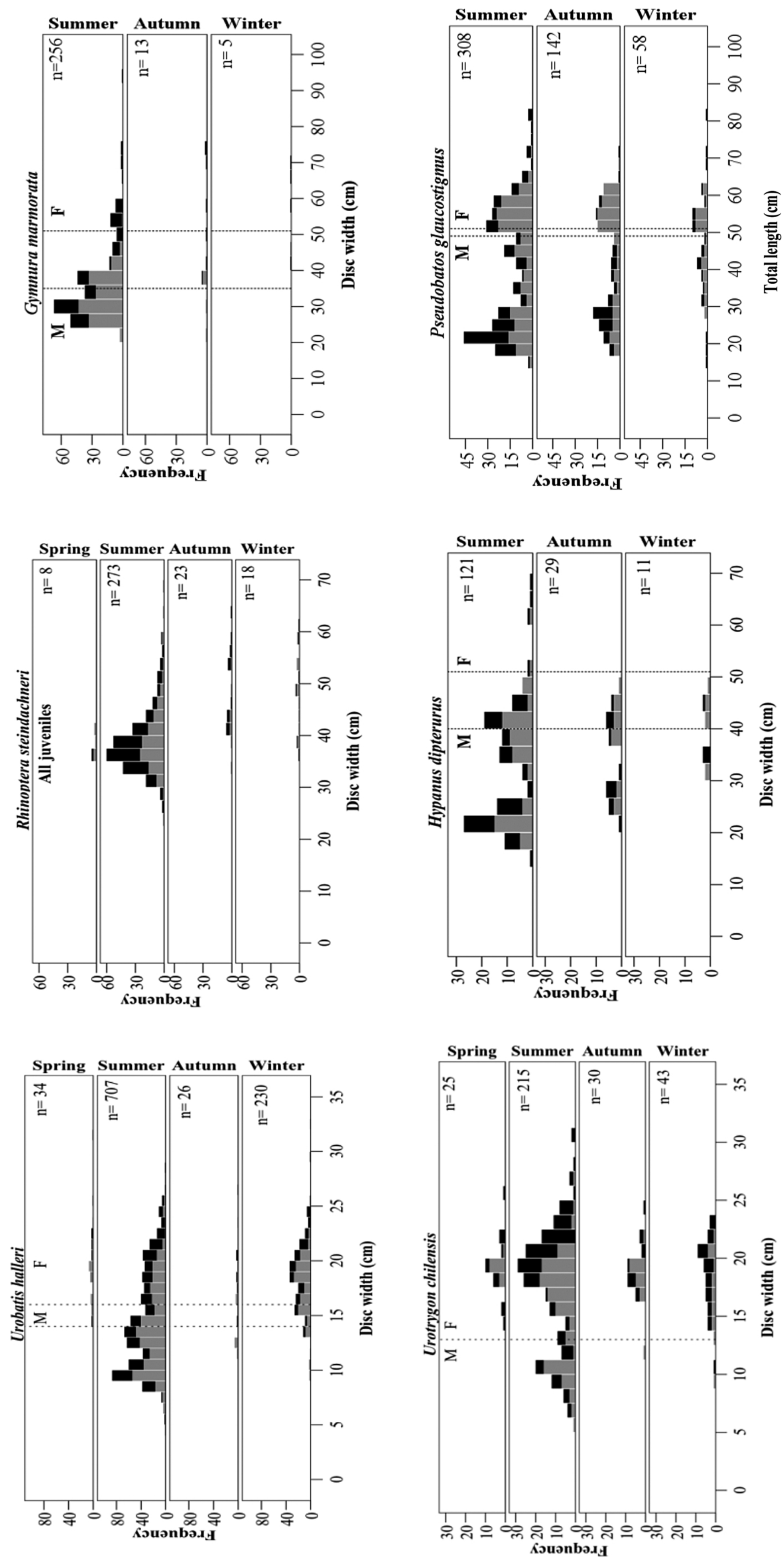


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**Fig. 3.** Size-frequency distributions of the six species most commonly caught in the prawn trawls by season, combined over all zones (30, 40 and 60) and depth strata during 2011–17 (*U. halleri*, *U. chilensis*, and *R. steindachneri*) or 2011–16 (*H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*). The females are shown as black bars and males as grey bars, and the two dashed lines represent the sizes at first maturity for the females (F) and males (M), separately.

Of 25 species, 24 were present in zone 30, 15 in zone 40, 16 in zone 60, and 15 were present in all zones (Table 4). The rays *Urobatis halleri, Urotrygon chilensis*, *Rhinoptera steindachneri, Hypanus dipterurus, Gymnura marmorata*, and *Pseudobatos glaucostigmus* were the six species present most often (Table 5).

### 3.2. Sex and size of the most common ray species

The sex and size-frequency compositions of these six most commonly collected species during the surveys are shown in Fig. 2. *Rhinoptera steindachneri* was represented by juveniles of both sexes in all zones and individuals ranged from 23 to 65 cm (DW). In contrast, *H. dipterurus* was represented mainly by mature males in all zones, and individuals ranged in size from 16 to 69 cm (DW). *Gymnura marmorata* was represented mostly by juvenile males in all zones, and individuals ranged from 9 to 92 cm (DW). *Pseudobatos glaucostigmus* was mainly represented by juvenile males and females in zones 30 and 40, and individuals ranged from 14 to 82 cm (TL). In contrast, *Urobatis halleri* and *Urotrygon chilensis* included mature individuals in all zones, mainly males for *Urobatis halleri* and both sexes for *Urotrygon chilensis*. Sizes ranged from 5 to 32 cm (DW), and from 7 to 31 cm (DW), respectively. For *R. steindachneri*, size at birth was estimated to be between 34 and 46 cm (DW) and for *Urobatis halleri*, between 7 and 9 cm (DW).

We found significant differences in the mean size between mature females and mature males for all five species tested: *Urobatis halleri* (females = 20.00 cm (DW), n = 267 and males = 19.00 cm (DW), n = 118, W = 79972, $P < 0.001$); *G. marmorata* (females = 61.28 cm (DW), n = 49 and males = 38.94 cm (DW), n = 69; W = 3094 15, $P < 0.001$); *P. glaucostigmus* (females = 62.88 cm (TL), n = 57 and males = 55.65 cm (TL), n = 176, W = 7174.5, $P < 0.001$); *Urotrygon chilensis* (females = 20.20 cm (DW), n = 165 and males = 18.40 cm (DW), n = 50, $t = 4.37$, $P < 0.001$; and, *H. dipterurus* (females = 62.42 cm (DW), n = 4 and males = 44.55 cm (DW), n = 40, W = 159, $P = 0.001$). For *R. steindachneri*, we did not test for differences because all specimens were juveniles.

The ratio of females to males (F:M) was not significantly different from 1:1 for 3 of 6 species tested; the exceptions were *Urobatis halleri* ($\chi^2 = 5.20$, df = 1, $P = 0.02$), *Urotrygon chilensis* ($\chi^2 = 4.18$, df = 1, $P = 0.04$) and *R. steindachneri* ($\chi^2 = 8.69$, df = 1, $P = 0.003$). For *Urobatis halleri* males predominated, and for the other two species females predominated.

Size-frequency distributions by sex were different among seasons (Fig. 3). For four of the six most frequently caught species, more juvenile males were present during summer, when most samples were taken. The two exceptions were *R. steindachneri,* of which more juvenile females than juvenile males were recorded; and *H. dipterurus*, of which more mature than immature individuals of both sexes were recorded.

The distribution of sizes for *Urobatis halleri*, *R. steindachneri* and *G. marmorata* was similar between depth strata. For *Urobatis halleri*, animals of both sexes and all size classes were more abundant at depths ≥12 m (Fig. 4). For *Urotrygon chilensis*, Fig. 4 indicates larger mature females are predominantly in depths ≥12 m. For *H. dipterurus* and *P. glaucostigmus*, the figure indicates that larger animals of both sexes may be more abundant in depths ≥12 m.

For five of the six species, there was a significant difference in the size distribution after FEDs were fitted (Table 5, Figs. 5 and 6). The exception was *P. glaucostigmus*, as discussed below. For the two small species, *Urobatis halleri* and *Urotrygon chilensis*, small juveniles < 15 cm and down to a disc width just larger than the net mesh size, continued to be retained in the survey trawl nets after the introduction of the FEDs, while larger individuals were less often caught. This effect, however was strong for *Urobatis halleri* and *Urotrygon chilensis* because of the small maximum sizes of these species, but the effect was not apparent for the other four species because for these species such small juveniles were not observed in the trawls before the FEDs were fitted. They all have larger sizes at birth and presumably rapid initial growth. The FEDs apparently allow larger rays (≥ about 15 cm) to escape from the cod end, but this effect reduces with the size of the animal, so that for the larger ray species *H. dipterurus*, *G. marmorata*, and *R. steindachneri*, less of the individuals in disc width from 15 to 35 or 40 cm and higher proportion of large animals caught is found when FEDs are present. The exception was the more fish-shaped guitarfish, *P. glaucostigmus* (ranging in length from 14 to 82 cm), where there was no significant change in the size distribution caught before and after the FEDs were installed. Fig. 6 shows that a slightly smaller proportion of the largest animals (> 55 cm length) and relatively more of the smallest individuals (< 24 cm) were caught when FEDs were used. While the changes are small and may have been produced by chance, it is noteworthy that these differences are in contrast to the pattern for the other large rays.

We were unable to estimate the effects on the length-frequency distribution of rays escaping through the TED hatch beneath the net, or outswimming the trawl, but our results indicate that all sizes of the two smallest rays pass through the TED grill into the cod end, and many much larger individuals of the larger rays are caught too. Furthemore, as the adult size range we recorded for the larger species is similar to those in the artisanal fishery (except for *R.steindachneri*, whose individuals caught in the artisanal fishery are larger) in the same area, this might apply to most sizes of all the rays.

## 4. Discussion

### 4.1. Species composition of the catch

In the present study, the number of species recorded exceeds those described in previous investigations of bycatch during prawn surveys (e.g., 3 species of sharks and 16 species of rays reported by López-Martínez et al., 2010; 3 species of sharks and 17 species of rays by Rodríguez-Romero et al., 2012). These differences may be because previous studies used commercial vessels, whereas the present study was based on research cruises, as no information is recorded from the commercial vessels during the closed season for prawn fishing. We have presented, for the first time, data from the closed seasons (which usually includes six months of the year, from early April to early September) for seven years. This intensive summer sampling has likely increased the number of species found, since many species of elasmobranchs, particularly rays, converge in summer to reproduce in the GoC (Salomón-Aguilar, 2015). Another factor to consider is the sampling area. Previous studies have reported information from either the south-eastern or the entrance region of the GoC, whereas we have data from both. We found, however that almost all the species recorded were present in zone 30, the south-eastern region of the GoC.

Several elasmobranch species in the prawn trawl bycatch are commonly caught as target species in the artisanal fisheries in the GoC. Such species include *Mustelus henlei*, *Rhizoprionodon longurio*, *Sphyrna lewini, Pseudobatos glaucostigmus, Rhinoptera steindachneri, Hypanus dipterurus,* and *Gymnura marmorata* (Márquez-Farías and Blanco-Parra, 2006; Bizzarro et al., 2009a; Smith et al., 2009; Torres-Herrera and Tovar-Ávila, 2014). Although the artisanal fisheries differ greatly from the prawn trawl fishery in terms of the fishing gear used and the fishing capacity of the vessels, the fishing zone and depth may explain the similarity in species caught, since most artisanal elasmobranch fishing is

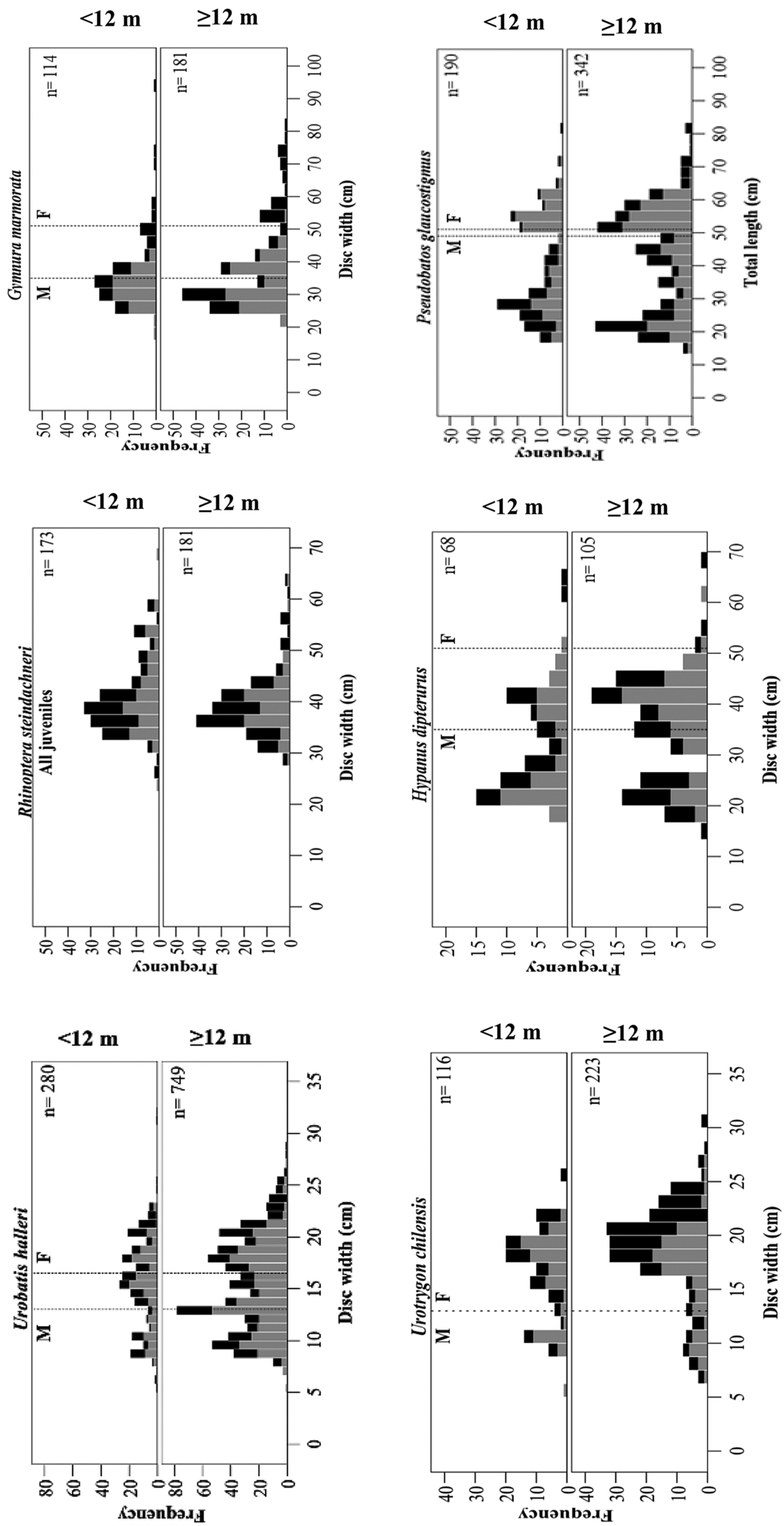


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**Fig. 4.** Size-frequency distributions of the six species most commonly caught in the prawn trawls by depth stratum (< 12 m, ≥12 m), combined over all zones (30, 40 and 60) and seasons during 2011–17 (*U. halleri*, *U. chilensis*, and *R. steindachneri*) or 2011–16 (*H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*). The females are shown as black bars and males as grey bars, and the two dashed lines represent the sizes at first maturity for the females (F) and males (M), separately.

demersal in the Gulf of California (Bizzarro et al., 2009b). Both prawn trawlers and artisanal shark fishers operate at similar depths along the coast of Sinaloa and Nayarit (> 4 m to 40 m and sometimes deeper) (Márquez-Farías and Blanco-Parra, 2006; DOF, 2013).

An important issue is the large number of batoid species (21) compared to the number of shark species (4) caught by prawn trawls during our study. The morphological characteristics of rays (e.g., dorsal spiracles) allow them to be associated with the bottom (e.g., *Urobatis* halleri and *Urotrygon chilensis*) or to explore the bottom of the continental shelf (e.g., *R. steindachneri* and *Mobula munkiana*). Furthermore, based on Bizzarro et al. (2007), 2009a and Bizzarro et al. (2009d), we note that the artisanal fishery of the GoC catches all of the ray species caught by prawn trawls, but also catches many more species of sharks. As strong swimming animals, we consider most sharks can readily outswim the relatively slow prawn trawls, which suggests much lower catchabilities for the sharks than for the rays by prawn trawling.

The majority of species analysed are in the "Data Deficient" (56 %) category, and the rest of the species are categorized as "Vulnerable" (4%), "Endangered" (4%), "Near threatened" (16 %) or "Least Concern" (20 %) according to the IUCN Red List (IUCN, 2019). We have added useful data for the "data deficient" species, and some might be classed as threatened because of low catches of small rays in the artisanal fisheries, as the bycatch of prawn trawls has not been extensively examined to date. Though most species we recorded have low commercial value, the prawn trawl fishery is clearly an important source of additional fishing mortality for these species. The impact of this fishery on these bycatch species, however is not known. In the same way, the non-fishing period of this fishery represents an indirect protection measure for some species, at least during some months of the year, that would need to be considered in an evaluation of the populations. The previously unavailable information we provide should allow a future detailed estimation of the fishing stressors, which may severely affect populations of some elasmobranchs in the GoC, as has happened in other parts of the world (Last et al., 2011). Other aspects, such as spatio-temporal distributions of species relative to oceanographic conditions and the ecology of the region, and the vulnerability of these species to climate change should be considered. Such ideas will be explored in subsequent papers.

### 4.2. Seasonality and reproductive strategies

It has been difficult to precisely determine the number of species of elasmobranchs present and their size-frequency distributions by season in Mexico (Bizzarro et al., 2009a). Here, we have recorded the number of species present in each zone and the distribution of sizes of the most frequently-caught species over several years for all seasons, in particular during summer.

Some of the most frequently caught species such as *Urobatis halleri* and *Urotrygon chilensis* tended to appear more frequently in summer and winter, whereas others (*H. dipterurus*, *R. steindachneri*, and *G. marmorata*) were caught more often in summer. These patterns might be related to environmental factors; when temperatures are warmer in the GoC some species may migrate to nearshore and inshore waters in the GoC to mate or to give birth (Salomón-Aguilar, 2015). Also, the sex ratio of the mature animals was different from 1:1 for *Urobatis halleri*, *Urotrygon chilensis,* and *R. steindachneri*. Differences in the frequency of occurrence and sex ratio may be related to their reproduction strategies, breeding season (Bizzarro, 2005; Salomón-Aguilar, 2015; Lara-Mendoza, 2016), and segregation according to stages or sex (Walker, 2005a).

We determined a size at first maturity for *Urobatis halleri* similar to the size at first maturity and at 50 % maturity found in other regions in the Mexican Pacific (Serrano-Acevedo, 2007) and in nearby areas (Mull et al., 2010). For *Urotrygon chilensis,* the size at first maturity we observed is smaller than that reported by De la Rosa-Meza (2010) in the GoC. Likewise, we found specimens of *G. marmorata* with size at first maturity smaller than that observed by Dávila-Ortiz (2002). For *P. glaucostigmus* the size at first maturity was smaller than that reported by De la Rosa-Meza (2010) and similar to the mean size at maturity reported by Lara-Mendoza (2016). For *H. dipterurus*, a common component of artisanal elasmobranch fisheries in western Mexico, we recorded a size at first maturity smaller than the size observed in the Bahia Magdalena lagoon in the western part of the GoC (Smith et al., 2007). Variations in size at maturity among populations, however, are common for chondrichthyan species because of differences in food availability, habitat and environmental conditions, or sex (Walker, 2005b), and the effects of length-selectivity in the fishery (Walker, 2007). The fact that we did not record mature specimens of *R. steindachneri* may be due to escape by larger individuals, as discussed below, implying that larger, mature fish are only caught by other fisheries such as the artisanal fishery (Bizzarro et al., 2009a), but it may indicate too that this part of the population is not available in our study area or on the sea bed where the trawl fishery operates.

We recorded the smallest size at birth to date for two species for our study area (Bizzarro et al., 2007; Burgos-Vázquez et al., 2019). Based on the largest embryos and smallest free-swimming individuals of *R. steindachneri*, size at birth is between 34 and 46 cm (DW), but births possibly occur at smaller sizes. López-López (2018) determined that individuals of *R. steindachneri* from 37.5–42.9 cm (DW) were one year old. We do not consider the possibility of pregnant females aborting in response to capture because we did not record mature females. For *Urobatis halleri,* based on the largest embryos and smallest free-swimming individuals, size at birth is between 7 and 9 cm (DW), but births may occur at smaller sizes. Diliegros-Valencia (2019) determined that animals from 8 to 9 cm (DW) were one year old, whereas Serrano-Acevedo (2007) reported neonates of 4 cm (DW) in Sonora, Mexico.

### 4.3. Size-frequency distributions of the most common ray species

Size classes of elasmobranchs caught in the GoC vary depending on the fishery and the fishing area in which they are caught (Bizzarro et al., 2009a). We found a wide range of sizes for the most frequently collected species. In addition, we have now documented size-frequency distributions for the zones and trawl depths in the south-eastern and entrance region. We note that adult size ranges of the most frequently collected species in each zone were similar to those reported for the artisanal fishery near to our study area (Bizzarro et al., 2007, 2009a; Bizzarro et al., 2009d). In contrast, juvenile size ranges were similar to those that have been reported for prawn trawl fishing in our study area (Nieto-Navarro et al., 2010; Lara-Mendoza, 2016). This suggests that mature animals of some (commercial) species are caught mainly by the artisanal fishery, whereas the prawn fishery catches more juveniles and more of the small species.

We found that larger individuals of some species appear to be more abundant in deeper water (≥12 m). This applies to *Urotrygon chilensis* females, and perhaps to both sexes of *H. dipterurus* and *P. glaucostigmus*. All size classes of *Urobatis halleri* appear to be more common at depths ≥12 m. The abundances and size distributions of *G. marmorata* and *R. steindachneri*, however appear to be similar in both depth strata. For the last two of these species, we consider that their larger body sizes compared to the small round rays allow them to move easily between inshore and offshore waters (Parson et al., 2011; Guida et al., 2017).

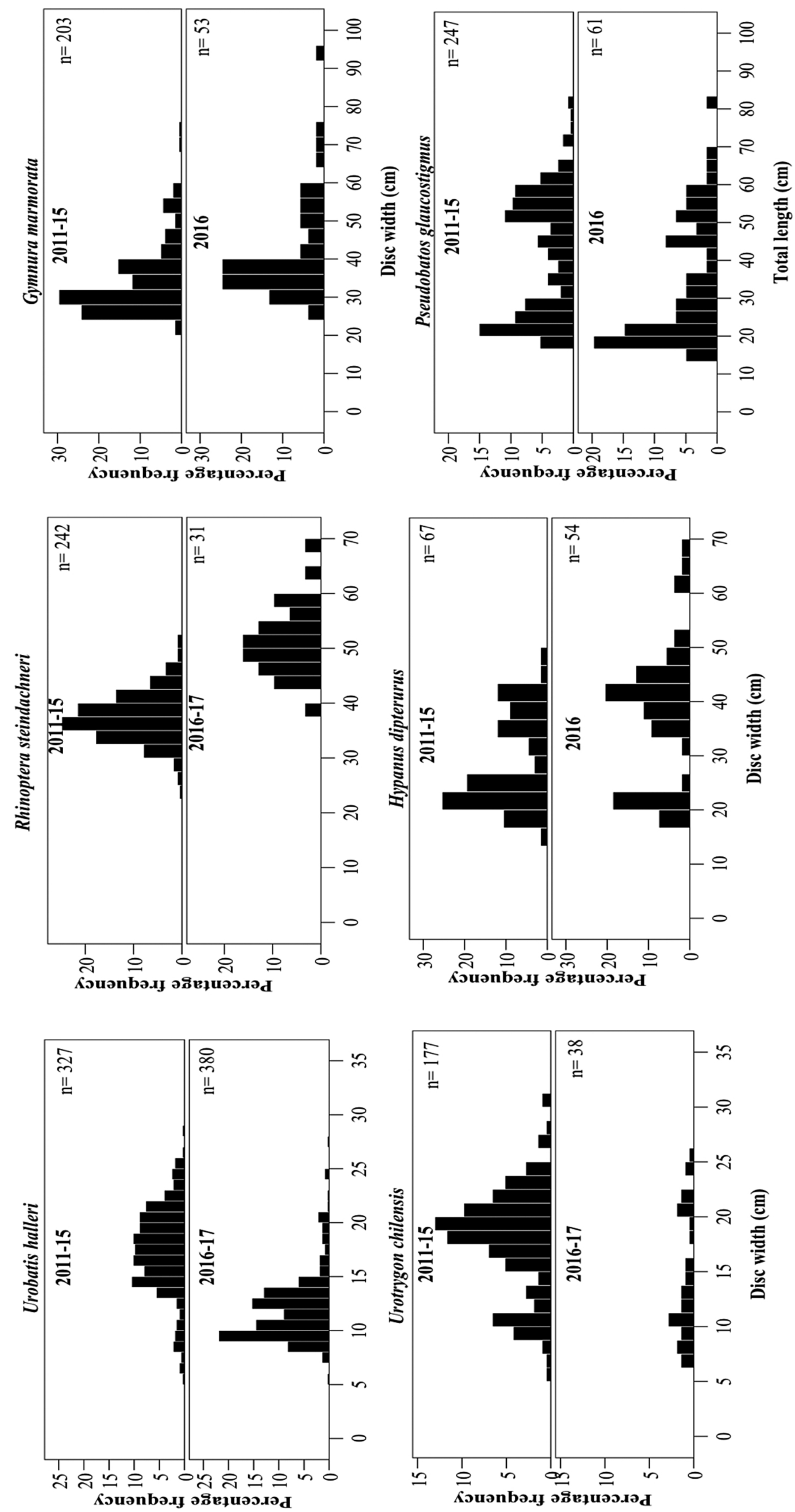


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**Fig. 5.** Size-frequency distributions of the six species (females and males combined) most commonly in the prawn trawls by period (before and after the adoption of fish exclusion devices), combined over all zones (30, 40 and 60), seasons, and depth strata during 2011–17 (*U. halleri*, *U. chilensis*, and *R. steindachneri*) or 2011–16 (*H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*).

For *Urobatis halleri* and *Urotrygon chilensis*, biological information is scarce, but based on the life-history strategies of *Urobatis halleri*, we hypothesize that young rays of *Urotrygon chilensis* remain close to shore and gradually move seaward with growth, and perhaps they segregate by sex as *Urobatis halleri* does (Babel, 1967). Mature females of *Urotrygon chilensis* are mainly distributed in offshore waters (Guzmán-Castellanos, 2015), but may become exposed to commercial prawn trawling when moving to inshore waters.

### *4.4. Size selectivity associated with trawl towing speed, TEDs, and FEDs*

Although mesh size in the cod end of a prawn trawl net can be regulated to allow escapement of small prawns and other small animals, it is not feasible to control the mesh size for the escapement of elasmobranch species or other large animals through the cod end meshes. However, other features of a prawn trawl allowing escapement that affect the size selectivity for various species by the net include the slow speed of the trawls, a ‘tickler’ chain ahead of the net, and the fitting of a TED or FED, or both. The slow trawl speed is likely to select for small rather than large animals, as the larger animals may be able to outswim the trawl nets. Similarly, the TED is likely to select for small rather than large animals, as large animals such as turtles and potentially some rays and sharks may be caught on the grill and forced out through the TED hatch, while smaller animals pass through the TED grill into the cod end. Once entrapped in the cod end, an animal, depending on its size, condition and swimming behaviour, might escape through a FED before it becomes exhausted or being constrained or crushed as the cod end fills with prawns, other bycatch, and debris.

As TEDs have been fitted since 1996, we were unable to test for their effect, but we were able to test for the effect of FEDs as they were fitted during the period of our survey data. The data cover only one or two years after FEDs were fitted, so that the post-FED data might be affected by short-term changes such as a strong year class and movement patterns of a species, but we have found consistent results for a number of species. Unlike invertebrate and teleost species, it is unusual for elasmobranchs to exhibit observable inter-annual changes in cohort strength. Our analyses suggest that the smallest-sized rays (< 15 cm disc width) do not readily escape, as we show for the small species *Urobatis halleri* and *Urotrygon chilensis*. These small juveniles may stay close to the bottom, or be unable to escape through the FED hoop opening by swimming faster than the trawl speed. For the larger species *G. marmorata*, *H. dipterurus* and *R. steindachneri*, the FED appears to allow 15–40 cm disc width animals to escape more often than larger animals. The reduction in the escapement with size for these three rays may be explained by increasing width across the pectoral fins (disc width), such that they eventually reach a width where they cannot readily fit through the 40 cm maximum diameter of the FED. For *P. glaucostigmus*, on the other hand, the width across the pectoral fins is much narrower, and animals of all or most sizes can presumably fit through the FED. However, this species may remain at the bottom of the cod end preventing their escape through the FED (if this is located at the top as in our surveys), so that no significant changes in the size-frequency composition were observed in relation to the device. It is also possible, however, that larger animals of this species are partly excluded by the bars of the TED, and this explains the lack of any significant change after the FEDs were fitted. In fact it is possible that the TED excludes some larger individuals of all the large rays from passing into the cod end, as we do not know if these were caught in the body of the net before the TED grill, rather than in the cod end. It would be useful to record, in future surveys, whether elasmobranchs are found in the body or the cod end of the net. Nevertheless, the reduction in relative numbers of 15–40 cm disc width rays after the FEDs were fitted raises the question of whether ray escapement could be improved by increasing the size of the elliptical ring of the FED. Such changes are unlikely to affect the catchability of prawns.

Although ignored by most studies (Cadrin et al., 2016), the size-selectivity of the fishing gear, including the bycatch escape devices, may have profound effects on the size-frequency distributions of animals in the catch (as we have shown) and also in the wild population through size-selective fishing mortality (Ricker, 1969). Sampling bias associated with size selectivity of the gear used for the scientific collection of samples occurs where the size-frequency distribution in the catch is not representative of the size-frequency distribution in the population. Size-selective fishing mortality, on the other hand, occurs where the size-frequency distributions of the various cohorts in the wild population change in response to fishing. Size-selective fishing mortality, together with sampling bias can lead to severe distortion of growth curves through the phenomenon of apparent change of growth rate (Lee, 1912; Ricker, 1969; Walker et al., 1998) and also to distortion of maturity and maternity ogives (Walker, 2007).

A better understanding of the relative contributions of trawl speed, TEDs and FEDs on the size-frequency distributions of the catch and wild population for each of these species could be achieved by an experimental approach during the summer survey. The approach would require variously repeating the standard procedure with two standard prawn trawl survey nets without either of the TED or FED, with only the TED, with only the FED, and with both the TED and FED. Ideally, two nets would be used where the TED and FED can be readily removed or inserted so that these options can be compared in pairs. In addition to the variables presently recorded, each animal should be measured. Although the tow time of the trawls should be standardised as in the present study to provide accurate catch per unit effort data as a measure of the relative abundance of the bycatch species. Further information on size-selectivity could be achieved by having two or three different trawl speeds, and different spacing of the grill bars of the TED and different position of FEDs, in the upper or lower side of the net.

## 5. Conclusions

### *5.1. What do we know now that we did not know before?*

Our analysis of available data on bycatch collected during fishery-independent prawn demersal catch surveys has provided information on the species of elasmobranchs that may be taken as bycatch during prawn trawling, particularly in the closed period when prawn trawling is prohibited, and information from commercial catches is not available. We have determined which species are most-frequently-caught by prawn trawl, in which zones, seasons and depth strata, and the size-frequency distributions in the catches of the most common species. We recorded the smallest size at birth observed for two species collected in the south-eastern and entrance region of the GoC. One is *Rhinoptera steindanchneri* (Pacific cownose ray), a primary component of artisanal elasmobranch fisheries in the Gulf of California and the southern Pacific coast of the Baja Peninsula (Mexico), indicating that this species is born at a smaller size than the size reported by other authors. The other species is *Urobatis halleri*, the most common species caught as bycatch, but with scarce biological information. Furthermore, our findings indicate that the species and length-frequency composition of the bycatch are influenced by trawl depth and fishing zones, and the mandatory exclusion devices. The recent implementation of fish escape devices appears to reduce the bycatch of adults of the small species and juveniles of the larger species in the prawn trawl fishery. We also suggest

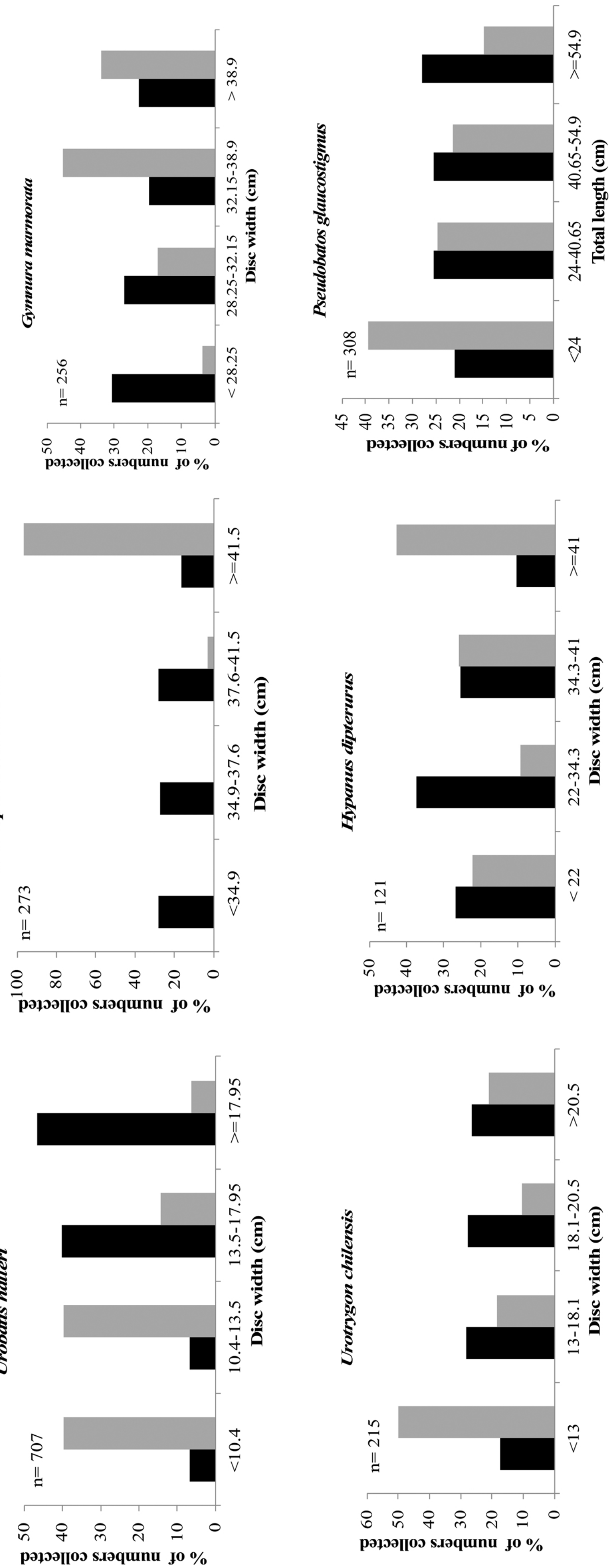


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**Fig. 6.** Percent-frequency quartile distributions for the six species (females and males combined) most commonly caught in the prawn trawls by period (before and after the adoption of fish exclusion devices), combined over all zones (30, 40 and 60), seasons, and depth strata during 2011–17 (*U. halleri*, *U. chilensis*, and *R. steindachneri*) or 2011–16 (*H. dipterurus*, *G. marmorata*, and *P. glaucostigmus*). The before adoption period is shown as black bars and after adoption period as grey bars.

much lower catchabilities for the sharks than for the rays caught during prawn trawling may be attributable to the slow towing speed of the trawls. Although further investigation is required, we have provided insight into how depth, seasons, and zone influence the bycatch of elasmobranchs caught during prawn trawling in the GoC. Also, this is the first time selectivity has been demonstrated in this fishery. Updates of biological information of elasmobranch species taken as bycatch as well as species-specific monitoring should be considered for the GoC.

## Author contributions

- The experimental design: KCGG, JTA, RWD, TIW
- Collected the samples: KCGG, DACA
- Preparation of the samples for analyses: KCGG, JTA, BVT
- Analyses of data: KCGG, RWD
- Contributed materials/ analysis tools: KCGG, JTA, RWD, TIW.
- Writing of the paper: KCGG, JTA, RWD, TIW.
- First author: KCGG

## Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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