BY-CATCH OF RAYS IN THE TRAWL FISHERY FOR ATLANTIC SEABOB SHRIMP *XIPHOPENAEUS KROYERI* IN SURINAME: HOW EFFECTIVE ARE TEDs AND BRDs?

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ABSTRACT

Tropical shrimp trawling fisheries are generally known to capture a large amount of unwanted organisms along with the targeted shrimp. To reduce this by-catch, the fishery for Atlantic seabob shrimp *Xiphopenaeus kroyeri* in Suriname uses nets fitted Turtle Excluder Devices (TEDs) and By-catch Reduction Devices (BRDs). It is unclear, however, to what extend these selectivity measures, designed to reduce capture of marine turtles and small roundfish respectively, are reducing by-catch of rays. Due to their life-history characteristics, rays (Batoidea; Chondrichthyes: Elasmobranchii) are generally vulnerable to overexploitation and several endangered species are known to occur in Surinamese waters. The objective of this study therefore is to assess the effect of the selectivity devices currently in place (TEDs and BRDs) on ray by-catch in the *X. kroyeri* trawling fishery. Hereto, sixty-five simultaneous catch-comparison hauls were conducted, comparing ray by-catch in trawls fitted with (*test*-net) and without (*control*-net) TEDs and BRDs.

Five different ray species occurred in the by-catch, *Gymnura micrura* and *Dasyatis guttata* being the dominant species. Overall, catch rate of rays was reduced by 36% in the *test*-net. Moreover, rays that did end up in the *test*-net codend were on average 21% smaller than those in the *control*-net. This confirms the presumption that rays escape through TEDs rather than BRDs, smaller individuals being able to pass through the TED, but larger ones being guided to the escape opening at the bottom of the net. TEDs were most efficient in excluding *Dasyatis geijskesi*, the largest ray species. By-catch of *D. guttata* was reduced as well, but exclusion was highly dependent on size. A similar, but less pronounced relationship between size and exclusion rate was observed for *G. micrura*. Nevertheless, large individuals of both species were relatively rare, the bulk of the ray by-catch being made up by small sized (< 40 cm body width) individuals of *G. micrura* and *D. guttata,* complemented with *Urotrygon microphthalmum*, a small-sized species. Although TEDs and BRDs seem efficient in reducing by-catch of large rays, they seem inappropriate to protect small-sized individuals, which are more abundant in the population. We therefore suggest that further by-catch related efforts in this fishery are concentrated on reducing the incidental capture of small-sized rays.

1. INTRODUCTION

In recent years, there has been increasing concern on the capture of chondrichthyans (cartilaginous fish including rays and sharks) in marine fisheries. In contrast to teleost fish, these animals are generally slow growing and long living, with late attainment of sexual maturity, low fecundity and low natural mortality. This K-selected life-history makes chondrichthyans particularly vulnerable to over-exploitation (Stevens et al., 2000). Moreover, rays and sharks are often of low economic value to fisheries targeting teleost fishes or invertebrates and hence discarded as unwanted by-catch. This mortality mostly remains unreported, resulting in deficient information on the populations and occurrence of chondrichthyans worldwide (Stevens et al., 2000; Bonfil, 1994).

In the fishery for Atlantic seabob shrimp *Xiphopenaeus kroyeri* (Heller, 1862) off Suriname, concerns have been raised on the by-catch of chondrichthyan fish. Like most wild-caught tropical shrimp, *X. kroyeri* is harvested with demersal fine-meshed trawl nets fished from outrigger trawlers. The fishery started in 1996 and the fleet now consists of about 20 vessels that operate 15 to 35 km offshore in Surinamese waters (FAO Statistical area 31). The vessels are allowed to fish only in a restricted area delimited by the 10 and 15 fathom isobaths (18 to 27 meters) and land ca. 10.000 tons of *X. kroyeri* per annum. To reduce unwanted by-catch, the trawls are obligatory equipped with Turtle Excluder Devices (TEDs) and By-catch Reduction Devices (BRDs, type square-mesh-window). BRDs have indeed proven to reduce the by-catch of small fishes in this fishery (Polet H. & et al, 2010), while TEDs seem highly efficient in reducing by-catch of marine turtles wherever they are applied (e.g. Brewer et al., 2006; Cox et al., 2007). Moreover, TEDs could theoretically exclude any organism larger that the spacing between the vertical bars. This seems relevant especially for rays (Batoidea, Chondrichthyes: Elasmobranchii), which to due to their large size and flattened body shape are expected to escape through TEDs, as has been observed in other fisheries (Brewer et al., 2006; Sala et al., 2011; Stobutzki et al., 2002). In the coastal waters of Suriname, different species of rays occur, some of them being globally endangered (red-listed DD or NT by IUCN) while their distribution in Suriname appears to overlap with the zone dedicated for the *X. kroyeri* trawling fishery (Willems T., unpublished data). As a result, this fishery can pose a threat to ray populations in the area and it is clearly desirable to avoid their capture.
Therefore, the aim of this study is to address:

(1) whether rays occur in the by-catch or are rather excluded from the trawls;
(2) whether exclusion is related to species identity and body size.

As such, the current research assesses the effectiveness of the net-adaptations currently in place (TED and BRD) in avoiding ray by-catch in the Suriname *X. kroyeri* trawling fishery.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted on the continental shelf off Suriname, inside the zone designated for *X. kroyeri* trawling fisheries. The area was characterised by substrates of mud to sandy mud and depths of 20 to 25m, bordered 6.169°N to 6.249°N, and 55.388°W to 55.841°W (Fig. 1). This area is frequented year-round by the *X. kroyeri* trawling fleet (Steven Hall, pers. comm.) and was therefore considered a suitable study area.

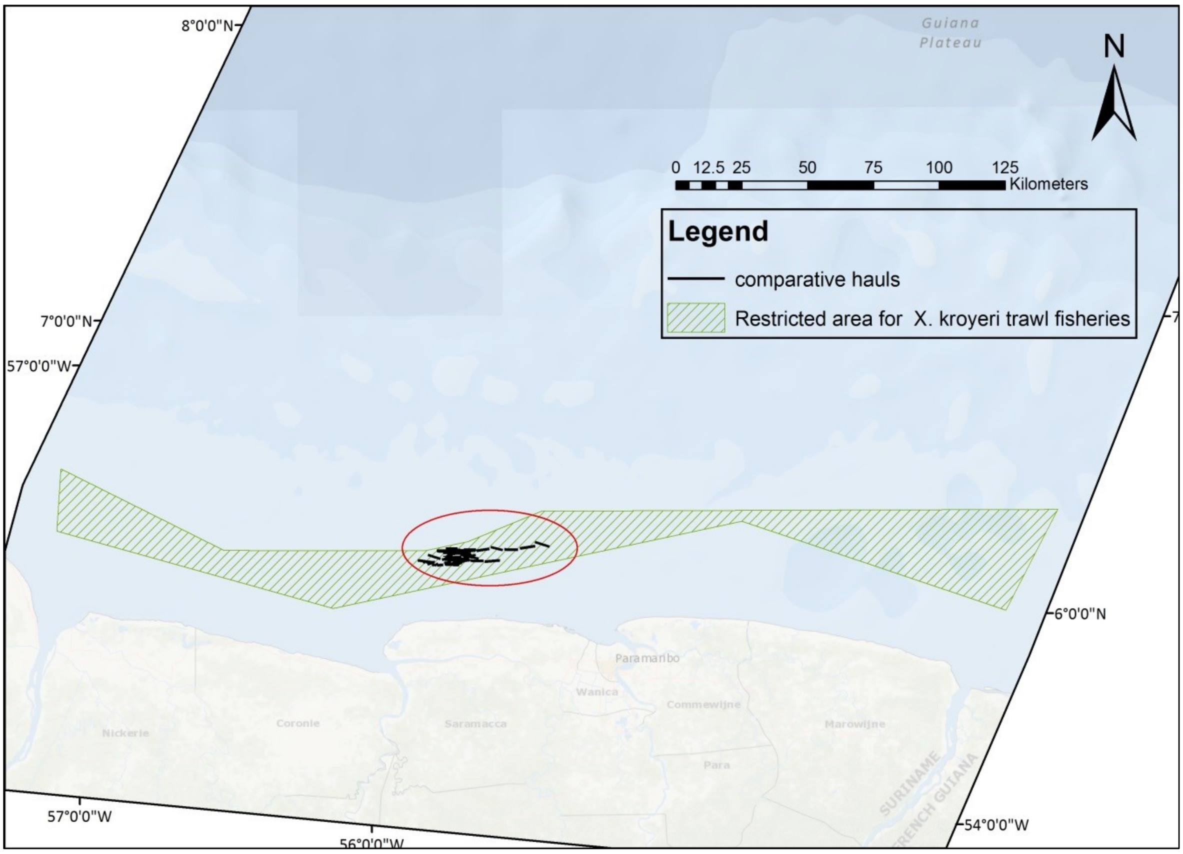


Figure 1. Study area

Figure 2. An outrigger trawler in the Suriname *X. kroyeri* trawling fleet ©Tomas Willems/ILVO

Figure 3. Simultaneous catch-comparison hauls comparing the *test*-net (r.) to the *control*-net (l.) ©Tomas Willems/ILVO

2.2 Gear specifications

Experimental hauls were done onboard FV Neptune 6, a typical 20-m, 425-hp 'Florida type' commercial outrigger trawler used in the Suriname *X. kroyeri* fishery (Fig.2). The vessel was equipped for twin-rig bottom-trawling, which involves dragging two steel-footed wooden doors and a mid-trawl sledge at either side of the vessel, each pair of doors fitted to two separate nets with mesh sizes ranging from 57mm in the body and wings, decreasing to 45mm in the codend. The nets have a vertical opening of ca. 2 m and a foot rope weighted with short (0.2 m) pieces of tickler chain. Horizontal spread between two doors is ca. 21 m. Nets are equipped with Turtle Excluder Devices (TEDs) and By-catch Reduction Devices (BRDs) in each of the four codends. The aluminum downward-excluding TED, positioned in an angle of approximately 45° just before the codend, has a bar-spacing of 100 mm, guiding larger animals to an escape opening at the underside of the net. The BRD is a square-mesh-window panel (11 x 11 meshes, 150 mm stretched mesh size) in the upper side of the codend (Fig. 4).

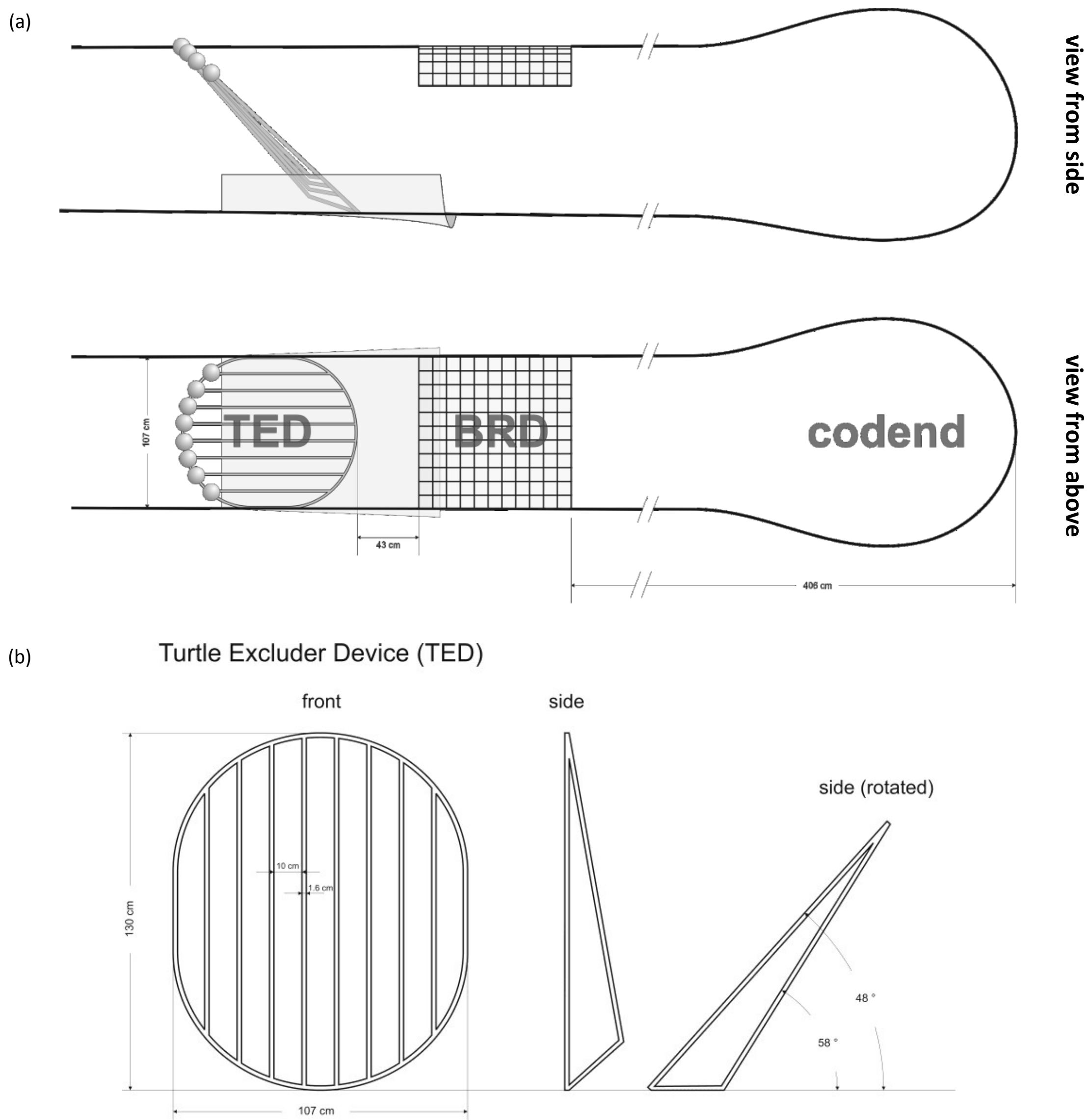


Figure 4. (a) *test*-net codend fitted with TED and BRD and (b) details of the TED ©Hans Hillewaert/ILVO

2.3 Sea trials

Sea trials were carried out, making simultaneous catch-comparison hauls between a 'normal' trawl fitted with TED and BRD in both codends (the *test*-net) and another without TEDs and BRDs but otherwise completely similar (the *control*-net) (Fig.3). Hauls were conducted on eight sampling days, spread between February 2012 and April 2013 accounting for possible temporal variation in the occurrence of rays in the study area. At the start of each sampling day, the trawl of either port or starboard side was modified to fish as *control*-net by removing the TEDs and attaching codends without BRDs. In this configuration, 7 to 10 consequent hauls were carried out per day, dragging the *test*-net alongside the *control*-net at a speed of 2.5 to 3 knots. In contrast to typical 4 to 5 hours dragging time, hauls were limited to a maximum of 2 hours to reduce the risk of injury or mortality of vulnerable species (e.g. sea turtles) in the *control*-net. Apart from this time restriction, hauls were conducted under commercial fishing circumstances. At the end of each haul, both nets where brought up and emptied on deck, assuring separation between catches of *test*- and *control*-net. Rays were manually sorted out, and all individuals identified to species and measured (maximum body width) to the nearest centimetre.

2.4 Data analysis

Analysis of count data

Ray catches were recalculated to catch rate (individuals h^{-1}). For each ray species, differences in mean catch rate between *test*- and *control*-net were analyzed using parametric paired *t*-tests. To assess differences in mean body size between the two nets, Mann-Whitney U test were carried out on size data, as assumptions were not met to perform Student's *t*-test. Analyses were carried out using Statistica (StatSoft). Ray communities caught in both nets were compared using an ANOSIM analysis in PRIMER-E (Clarke & Gorley R.N., 2006).

Analysis of size data

The proportion ϕ(S) of rays (a certain ray species) retained by the *test*-net at body size S can be expressed for each size and each haul as:

$$\phi(S) = N_{S,test}/(N_{S,test} + N_{S,control})$$

where $N_{S,test}$ and $N_{S,control}$ are number of rays at size S (body width) measured for the *test*-net (with TEDs and BRDs) and the *control*-net (without TEDs and BRDs) respectively. A value of $\phi = 0.5$ indicates that there are no differences in catch in numbers between the two nets at size S. The catch at size proportion ϕ(S) for rays from the two nets was analyzed using the Generalized Linear Mixed Model (GLMM) with binomial distribution and size (S) as explanatory variable(s) and ϕ as the response variable, according to the method described by Holst & Revill (2009). The catch comparison curves vary among hauls, potentially in a length-specific manner. In addition to the fixed effects, inter-haul correlation was incorporated into the models by the inclusion of random intercept and/or slope effects. The concept of random effects is well known for generalized linear mixed models in fisheries science (Venables & Dichmont, 2004). The random effect structure was selected using the Akaike information criterion (AIC) and restricted maximum likelihood (Zuur *et al.*, 2009: 122) . The random effect polynomial regression GLMM was used to fit catch comparison curves for the expected proportions of the catch retained by the *test*-net, after logit transformation, as:

$$\text{logit}[\phi(S)] = \beta_0 + \beta_1 S + \beta_2 S^2$$

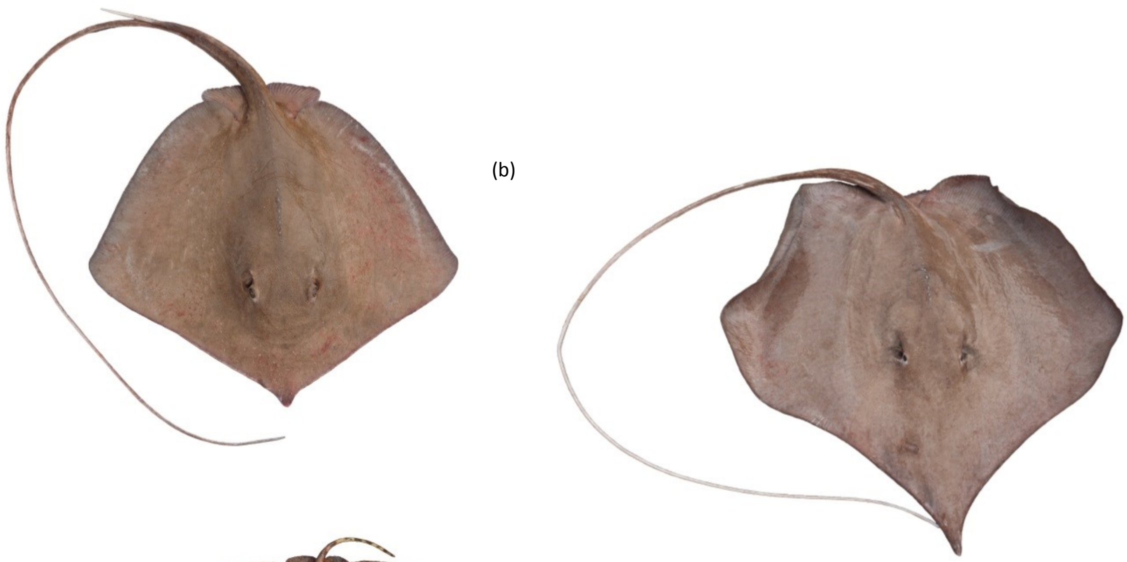
The preferred random effect model was used for model selection of the fixed effects (constant, linear and/or 2[nd] order) and was based on AIC as well. The analysis was performed using R statistical environment.

3. RESULTS

3.1 Sea trials

Sixty-five successful catch-comparison hauls with an average duration of 1h16" were carried out (Table 1), catching a total of 3181 rays of five different species: Smooth butterfly ray (*Gymnura micrura*), Longnose stingray (*Dasyatis guttata*), Smalleyed round stingray (*Urotrygon microphthalmum*), Sharpsnout stingray (*Dasyatis geijskesi*) and Cownose ray (*Rhinoptera bonasus*). Additional chondrichthyan fish species caught, but not considered in the analyses, were Brazilian electric ray (*Narcine brasiliensis*), Smalleye Smoothhound (*Mustelus higmani*) and Chola guitarfish (*Rhinobatos percellens*). No sea turtles were caught.

(a) (b)



(c)

Figure 5. Three large-bodied ray species caught during the study: (a) *Dasyatis guttata,* (b) *Dasyatis geijskesi,* (c) *Gymnura micrura* © Tomas Willems/ILVO, Hans Hillewaert/ILVO

Table 1 Summary of haul data

Haul	Date	Shooting time	Hauling time	Duration (h:min)	Postion shot				Position hauled			
1	21/02/2012	7:46	8:50	1:04	6.206	°N	55.806	°W	6.192	°N	55.762	°W
2	21/02/2012	9:10	10:05	0:55	6.190	°N	55.758	°W	6.196	°N	55.715	°W
3	21/02/2012	10:15	11:25	1:10	6.193	°N	55.711	°W	6.192	°N	55.664	°W
4	21/02/2012	11:40	12:51	1:11	6.187	°N	55.668	°W	6.178	°N	55.723	°W
5	21/02/2012	13:06	14:28	1:22	6.174	°N	55.733	°W	6.174	°N	55.710	°W
6	21/02/2012	14:45	15:55	1:10	6.174	°N	55.724	°W	6.177	°N	55.714	°W
7	21/02/2012	16:10	17:20	1:10	6.175	°N	55.699	°W	6.173	°N	55.726	°W
8	21/02/2012	17:35	18:51	1:16	6.177	°N	55.718	°W	6.175	°N	55.742	°W
9	21/02/2012	19:10	20:30	1:20	6.174	°N	55.747	°W	6.171	°N	55.699	°W
10	21/02/2012	20:50	22:30	1:40	6.177	°N	55.701	°W	6.180	°N	55.689	°W
11	24/04/2012	7:34	8:43	1:09	6.189	°N	55.841	°W	6.181	°N	55.791	°W
12	24/04/2012	9:12	10:23	1:11	6.182	°N	55.782	°W	6.181	°N	55.806	°W
13	24/04/2012	10:43	11:58	1:15	6.186	°N	55.795	°W	6.178	°N	55.798	°W
14	24/04/2012	12:25	13:32	1:07	6.174	°N	55.807	°W	6.181	°N	55.787	°W
15	24/04/2012	15:30	16:54	1:24	6.181	°N	55.813	°W	6.183	°N	55.796	°W
16	24/04/2012	17:07	18:41	1:34	6.179	°N	55.800	°W	6.182	°N	55.813	°W
17	24/04/2012	19:02	20:00	0:58	6.180	°N	55.815	°W	6.183	°N	55.822	°W
18	24/04/2012	20:45	22:31	1:46	6.180	°N	55.817	°W	6.186	°N	55.822	°W
19	28/05/2012	22:22	23:58	1:36	6.210	°N	55.730	°W	6.213	°N	55.669	°W
20	29/05/2012	4:00	6:00	2:00	6.213	°N	55.663	°W	6.207	°N	55.661	°W
21	29/05/2012	6:23	7:53	1:30	6.210	°N	55.668	°W	6.207	°N	55.678	°W
22	29/05/2012	8:05	9:42	1:37	6.208	°N	55.695	°W	6.201	°N	55.675	°W
23	29/05/2012	9:55	11:40	1:45	6.205	°N	55.681	°W	6.206	°N	55.683	°W
24	29/05/2012	11:53	13:44	1:51	6.212	°N	55.679	°W	6.205	°N	55.677	°W
25	29/05/2012	13:55	15:53	1:58	6.203	°N	55.671	°W	6.202	°N	55.664	°W
26	25/07/2012	5:00	6:27	1:27	6.213	°N	55.716	°W	6.208	°N	55.659	°W
27	25/07/2012	6:50	8:30	1:40	6.206	°N	55.641	°W	6.182	°N	55.718	°W
28	25/07/2012	8:47	10:33	1:46	6.183	°N	55.736	°W	6.181	°N	55.735	°W
29	25/07/2012	10:48	12:27	1:39	6.181	°N	55.726	°W	6.179	°N	55.750	°W
30	25/07/2012	12:50	14:25	1:35	6.177	°N	55.770	°W	6.173	°N	55.779	°W
31	25/07/2012	14:40	16:26	1:46	6.169	°N	55.792	°W	6.174	°N	55.784	°W
32	25/07/2012	16:48	18:14	1:26	6.171	°N	55.777	°W	6.173	°N	55.784	°W
33	25/07/2012	18:40	19:51	1:11	6.171	°N	55.775	°W	6.173	°N	55.753	°W
34	3/10/2012	5:45	6:55	1:10	6.202	°N	55.720	°W	6.203	°N	55.739	°W
35	3/10/2012	7:15	8:20	1:05	6.211	°N	55.732	°W	6.198	°N	55.735	°W
36	3/10/2012	8:38	9:55	1:17	6.203	°N	55.749	°W	6.199	°N	55.748	°W
37	3/10/2012	10:10	11:30	1:20	6.199	°N	55.743	°W	6.208	°N	55.732	°W
38	3/10/2012	11:50	13:05	1:15	6.198	°N	55.735	°W	6.191	°N	55.735	°W
39	3/10/2012	13:19	14:35	1:16	6.200	°N	55.739	°W	6.199	°N	55.730	°W
40	3/10/2012	14:50	16:00	1:10	6.199	°N	55.738	°W	6.193	°N	55.747	°W
41	3/10/2012	16:20	17:40	1:20	6.191	°N	55.748	°W	6.183	°N	55.683	°W
42	1/11/2012	5:55	6:55	1:00	6.182	°N	55.715	°W	6.189	°N	55.672	°W
43	1/11/2012	7:15	8:20	1:05	6.187	°N	55.675	°W	6.193	°N	55.733	°W
44	1/11/2012	8:40	9:44	1:04	6.197	°N	55.738	°W	6.199	°N	55.690	°W
45	1/11/2012	10:00	11:10	1:10	6.203	°N	55.683	°W	6.193	°N	55.631	°W
46	1/11/2012	11:25	12:35	1:10	6.200	°N	55.650	°W	6.213	°N	55.672	°W
47	1/11/2012	12:55	13:58	1:03	6.207	°N	55.688	°W	6.186	°N	55.663	°W
48	1/11/2012	14:15	15:20	1:05	6.187	°N	55.660	°W	6.185	°N	55.615	°W
49	1/11/2012	15:35	16:50	1:15	6.183	°N	55.611	°W	6.187	°N	55.558	°W
50	2/02/2013	7:40	8:44	1:04	6.221	°N	55.677	°W	6.225	°N	55.733	°W
51	2/02/2013	9:00	10:04	1:04	6.214	°N	55.735	°W	6.219	°N	55.694	°W
52	2/02/2013	10:15	11:20	1:05	6.219	°N	55.691	°W	6.225	°N	55.739	°W
53	2/02/2013	11:35	12:40	1:05	6.227	°N	55.744	°W	6.227	°N	55.704	°W
54	2/02/2013	12:55	14:05	1:10	6.223	°N	55.699	°W	6.216	°N	55.754	°W
55	2/02/2013	14:20	15:25	1:05	6.213	°N	55.753	°W	6.213	°N	55.712	°W
56	2/02/2013	15:40	16:50	1:10	6.217	°N	55.714	°W	6.220	°N	55.774	°W
57	2/02/2013	17:05	18:10	1:05	6.220	°N	55.775	°W	6.222	°N	55.733	°W
58	14/03/2013	6:30	7:30	1:00	6.223	°N	55.682	°W	6.224	°N	55.642	°W
59	14/03/2013	7:45	8:45	1:00	6.222	°N	55.644	°W	6.213	°N	55.697	°W
60	14/03/2013	9:00	10:00	1:00	6.215	°N	55.689	°W	6.225	°N	55.641	°W
61	14/03/2013	10:15	11:20	1:05	6.220	°N	55.640	°W	6.227	°N	55.595	°W
62	14/03/2013	11:32	12:32	1:00	6.232	°N	55.590	°W	6.222	°N	55.549	°W
63	14/03/2013	12:47	13:50	1:03	6.224	°N	55.543	°W	6.223	°N	55.496	°W
64	14/03/2013	14:05	15:10	1:05	6.228	°N	55.490	°W	6.235	°N	55.438	°W
65	14/03/2013	15:30	16:35	1:05	6.249	°N	55.438	°W	6.233	°N	55.388	°W

3.2 Count-based analysis

Occurrence of rays

Rays were found present year-round in the study area and were captured in every experimental haul, although catch rate differed considerably between sampling days (Fig. 6). In April 2012, on average 45 rays were caught per hour in the *control*-net, while in May 2012 this was only 6.3 individuals h^{-1}. This corresponds to a mean density of 4.3 to 0.6 rays ha^{-1} in the study area.

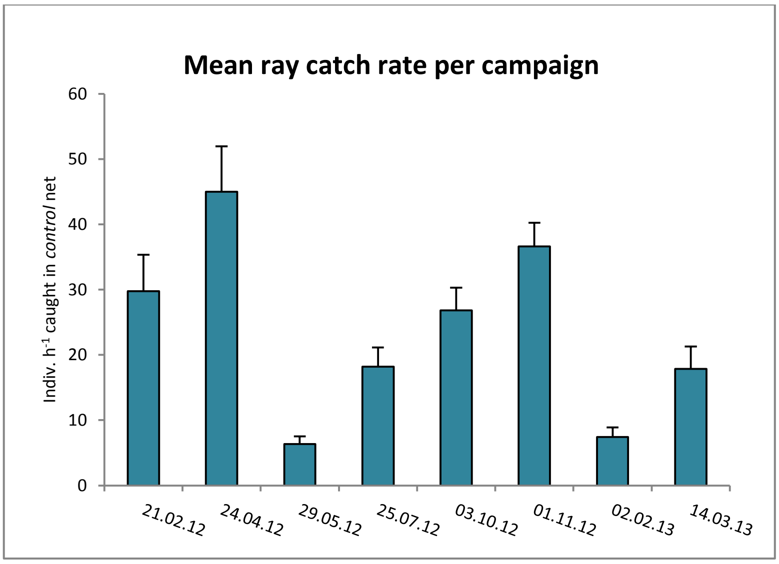


Figure 6. Mean (+SE) ray catch rate in the *control* net for each sampling day. *Test*-net data were not considered as they may be biased due to differences in escape rate between sampling days.

Species composition

Looking at the composition of ray by-catch, *Gymnura micrura* and *Dasyatis guttata* were the most common species, accounting respectively for 45% and 37.1% of all rays caught. *Urotrygon microphthalmum* (11.1%), *Dasyatis geijskesi* (6.3%) and *Rhinoptera bonasus* (0.6%) were less abundant.

A shift in ray by-catch composition occurred in the *test*-net compared to the *control*-net (Fig.7). The ray community caught in the *control*-net appeared significantly different from the *test*-net, although the difference was very small (ANOSIM; global R=0.053; sign. level 0.1%).

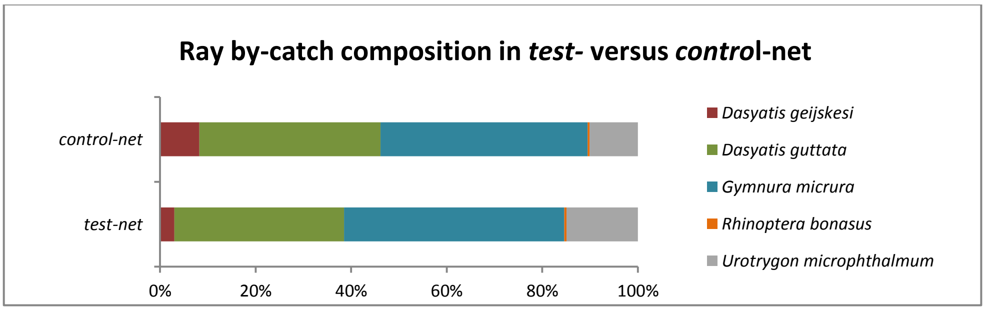


Figure 7. Composition of ray by-catch in the *test*-net compared to the *control*-net.

Catch rate comparison

Overall, the mean catch rate of rays (all species) was significantly reduced by 36.1% in the *test*-net (mean 15.3 indiv. h^{-1}) compared to the *control*-net (mean 23.9 indiv. h^{-1}; $p<0.001$; Table 2). Considerable and significant reduction in catch rates were observed for *Dasyatis geijskesi* (76.6%), *Dasyatis guttata* (40.2%) and *Gymnura micrura* (32.1%; all $p<0.001$; Table 2; Fig. 8). Catch rate reductions in *Rhinoptera bonasus* and *Urotrygon microphthalmum* were smaller and appeared not significant (Table 2; Fig. 8).

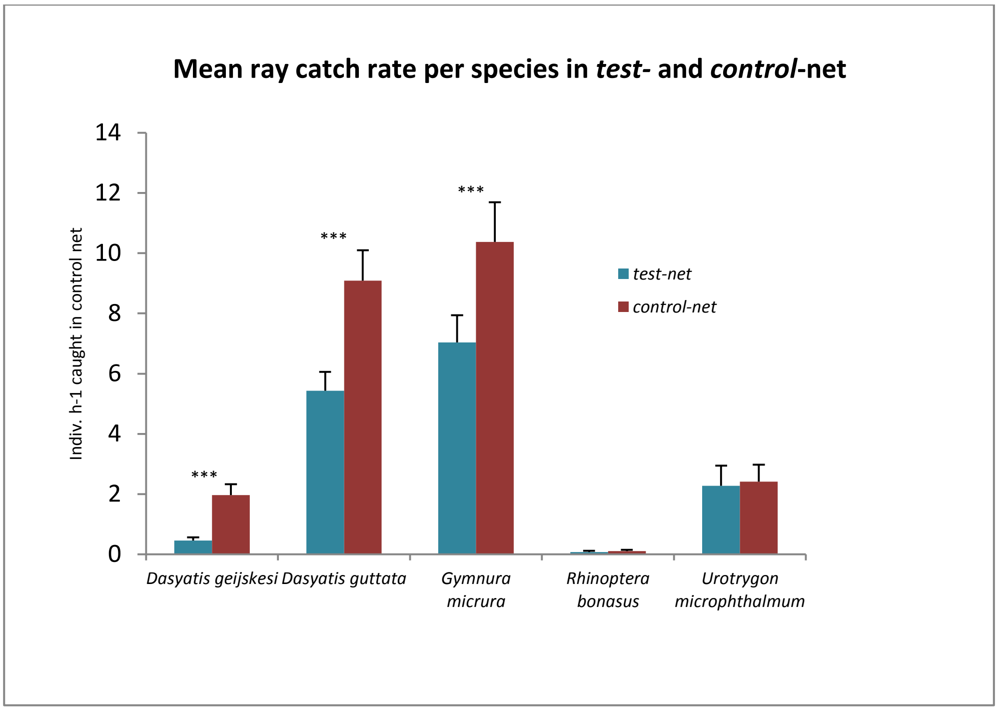


Figure 8. Mean (+SE) catch rate of all ray species in *test* and *control* nets. Significant differences in mean catch rate are indicated with asterisks (***; paried *t*-test; $p<0.001$).

Table 2 Catch rate (individuals h^{-1}) of five ray species in *test* and *control* nets and results of paired t-test comparing the mean catch rates.

	Dasyatis geijskesi		*Dasyatis guttata*		*Gymnura micrura*		*Rhinoptera bonasus*		*Urotrygon microphthalmum*		*All rays*	
Haul	*Control*	*Test*	*Control*	*Test*	*Control*	*Test*	*Control*	*Test*	*Control*	*Test*	*Control*	*Test*
1	1.9	0.9	12.2	2.8	12.2	11.3	0	0	15.9	20.6	42.2	35.6
2	0	0	1.1	0	3.3	1.1	0	0	2.2	2.2	6.5	3.3
3	0	0	0	0.9	3.4	2.6	0	0	1.7	0.9	5.1	4.3
4	1.7	0	10.1	7.6	25.4	16.1	0	0	0.8	1.7	38.0	25.4
5	2.2	0.7	17.6	3.7	38.8	27.1	0	0	5.9	7.3	64.4	38.8
6	0	0	3.4	3.4	22.3	16.3	0	0	7.7	6.0	33.4	25.7
7	0.9	0.9	1.7	2.6	11.1	13.7	0	0	2.6	2.6	16.3	19.7
8	1.6	0.8	3.2	4.7	17.4	16.6	0	0	2.4	8.7	24.5	30.8
9	3.0	0.8	4.5	0.8	14.3	9.8	0	0	9.8	1.5	31.5	12.8
10	0.6	1.2	6.0	5.4	25.2	15.6	0	0	3.6	2.4	35.4	24.6
11	0.9	0.9	37.4	14.8	32.2	27.8	0	0	0	0	70.4	43.5
12	2.5	0	12.7	7.6	22.0	32.1	0	0	0	0	37.2	39.7
13	2.4	0	24.0	4.0	49.6	8.0	0	0	0	0	76.0	12.0
14	1.8	1.8	14.3	6.3	26.9	26.9	0	0	0	0	43.0	34.9
15	0	0	6.4	0.7	23.6	5.7	0.7	0	0	0	30.7	6.4
16	0.6	0	11.5	1.9	21.7	5.1	0	0	0	0	33.8	7.0
17	2.1	0	8.3	7.2	38.3	14.5	1.0	0	0	0	49.7	21.7
18	1.7	0	4.5	2.8	11.9	10.8	1.1	0.6	0	0	19.2	14.2
19	0	0	0	0	0.6	1.9	0	0.6	0	0	0.6	2.5
20	0	1.0	2.0	2.0	5.0	5.5	0.5	0	0.5	0	8.0	8.5
21	0	0	2.0	2.0	2.7	1.3	0	0	0	0	4.7	3.3
22	0	0	1.2	0	4.9	5.6	0.6	0	0	0	6.8	5.6
23	0	0	0.6	0.6	8.6	1.1	0	0.6	0	0	9.1	2.3
24	0.5	0	0.5	1.6	2.2	2.2	1.6	0.5	0.5	0	5.4	4.3
25	0	0.5	3.1	0.5	6.1	1.5	0.5	1.0	0	0	9.7	3.6
26	0	0	12.4	2.1	3.4	0	0	0	0	0	15.9	2.1
27	1.8	0	9.0	3.0	6.6	3.0	0	0	0	0	17.4	6.0
28	1.1	0	6.8	5.1	9.1	2.8	0	0	0	0	17.0	7.9
29	3.0	0	9.1	9.7	7.9	2.4	0	0	0	0	20	12.1
30	9.5	3.8	17.1	11.4	9.5	6.3	0	0	0	0	36.0	21.5
31	3.4	0.6	11.3	7.9	2.8	1.7	0	0	1.7	0	19.2	10.2
32	0	0	7.0	2.8	4.2	1.4	0	0	2.1	2.1	13.3	6.3
33	0.8	0	4.2	2.5	0.8	3.4	0	0	0.8	0	6.8	5.9
34	6.0	1.7	18.9	4.3	4.3	1.7	0	0	0	0	29.1	7.7
35	10.2	0	12.9	8.3	5.5	3.7	0	0	0	0	28.6	12.0
36	12.5	0	16.4	14.8	3.1	7.0	0	0	0	0	31.9	21.8
37	2.3	0	8.3	12.0	5.3	3.8	0	0	0	0	15.8	15.8
38	0.8	0	15.2	5.6	8.0	8.0	0	0	0	0	24.0	13.6
39	0.8	0	8.7	11.1	3.9	2.4	0	0	0	0	13.4	13.4
40	0	0	19.7	6.9	6.9	3.4	0	0	0	0.9	26.6	11.1
41	2.3	0	27.0	13.5	12.8	4.5	0	0	3.0	0.8	45.0	18.8
42	1.0	1.0	3.0	5.0	0	5.0	0	0	2.0	7.0	6.0	18.0
43	0.9	0	2.8	5.5	2.8	0.9	0	0	2.8	4.6	9.2	11.1
44	0	0	4.7	0.9	4.7	0.9	0	0	0.9	0	10.3	1.9
45	2.6	0	18.9	13.7	12.0	10.3	0	0	5.1	2.6	38.6	26.6
46	8.6	0	28.3	12.9	15.4	13.7	0	0	0.9	1.7	53.1	28.3
47	1.0	0	12.4	2.9	7.6	3.8	0	0	7.6	0	28.6	6.7
48	7.4	0.9	24.0	25.8	31.4	13.8	0	0	25.8	12.0	88.6	52.6
49	12.0	4.0	30.4	20	7.2	12.8	0	0	8.8	32.8	58.4	69.6
50	0	0	3.8	1.9	0.9	1.9	0	0	0	0	4.7	3.8
51	0	0	1.9	0.9	0.9	0	0	0	0	0	2.8	0.9
52	0.9	0	0.9	1.8	2.8	2.8	0	0	0	0	4.6	4.6
53	0	0	9.2	2.8	3.7	1.8	0	0	0	0	12.9	4.6
54	0	0.9	2.6	4.3	2.6	9.4	0	0	0	0	5.1	14.6
55	2.8	1.8	1.8	4.6	5.5	5.5	0.9	1.8	0	0.9	11.1	14.8
56	1.7	0	3.4	4.3	0	3.4	0	0	0	0	5.1	7.7
57	0.9	0	7.4	11.1	4.6	3.7	0	0	0	0	12.9	14.8
58	0	0	2.0	5.0	4.0	4.0	0	0	1.0	3.0	7.0	12.0
59	1.0	1.0	5.0	4.0	0	0	0	0	2.0	0	8.0	5.0
60	0	0	5.0	3.0	3.0	1.0	0	0	1.0	0	9.0	4.0
61	0.9	0	8.3	3.7	3.7	2.8	0	0	1.8	2.8	14.8	9.2
62	0	0	5.0	5.0	9.0	3.0	0	0	9.0	14.0	23.0	22.0
63	0	2.9	4.8	1.9	10.5	10.5	0	0	5.7	1.0	21.0	16.2
64	1.8	0	4.6	3.7	9.2	3.7	0	0	10.2	4.6	25.8	12.0
65	5.5	1.8	8.3	3.7	9.2	7.4	0	0	11.1	3.7	34.2	16.6
Mean	2.0	0.5	9.1	5.4	10.4	7.0	0.1	0.1	2.4	2.3	23.9	15.3
SE	0.4	0.1	1.0	0.6	1.3	0.9	0	0	0.6	0.7	2.4	1.6
Red. by	**76.6%**		**40.2%**		**32.1%**		**26.7%**		**5.6%**		**36.1%**	
t-value	-4.58808		-5.12039		-3.61791		-0.79999		-0.25708		-5.55699	
p-value	<0.001		<0.001		<0.001		0.4267		0.79794		<0.001	

3.3 Size-based analysis

Mean size

The rays captured during the experiment had an average body width of 29.6 cm (+-0.3cm) but size varied greatly, the largest individual measuring 116 cm and the smallest one only 3 cm. Although considerable overlap was present, the five ray species showed marked differences in body size range (Fig. 9).

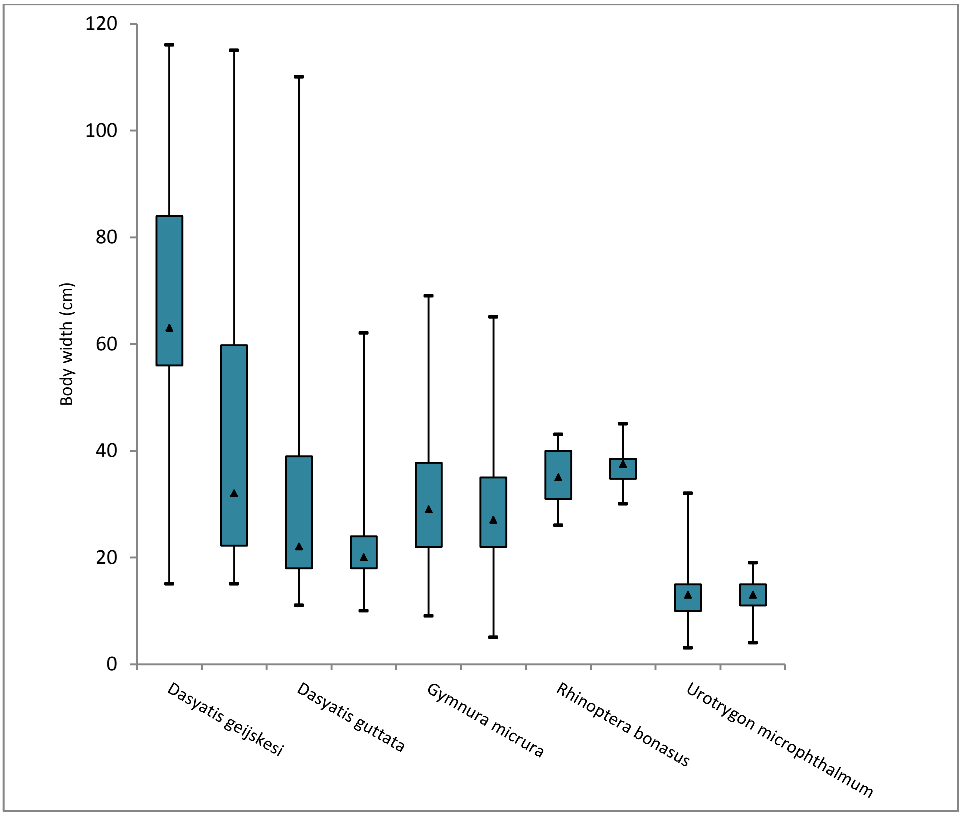


Figure 9. Box-and-whisker-plots showing minimum, maximum, 0.25 percentile, 0.75 percentile and median body width of the different ray species. For each species, left-hand boxes present *control*-net catches, right-hand boxes present *test*-net catches.

Size in test- versus control-net

Comparing the body width of rays captured in both nets, a significant overall 20.6%-reduction in mean body width was observed for rays caught in the *test*-net (mean 25.54 cm) relative to the *control*-net (mean 32.18 cm; p<0.001; Table 3). Looking at the individual species, a significant size reduction in the *test*-net catches was observed for *D. geijskesi* (37.8%) and *D. guttata* (22.7%).

Table 3 Analysis of mean body width variation between catches in *control* en *test*-net. Results of Mann-Whitney U Tests.

Species	*Control*-net mean body width (cm)	SE	*n*	*Test*-net mean body width (cm)	SE	*n*	Difference in mean body width	*P*
Dasyatis geijskesi	67.30	1.78	161	41.87	4.21	38	37.8%	<0.001
Dasyatis guttata	29.05	0.55	741	22.46	0.37	440	22.7%	<0.001
Gymnura micrura	32.36	0.45	858	30.57	0.49	572	5.5%	0.0595
Rhinoptera bonasus	35.45	1.71	11	36.88	1.69	8	-4.0%	0.8027
Urotrygon microphthalmum	12.68	0.31	181	12.47	0.24	171	1.6%	0.9945
All rays	32.18	0.42	1952	25.54	0.35	1229	20.6%	<0.001

Body width and escape ratio

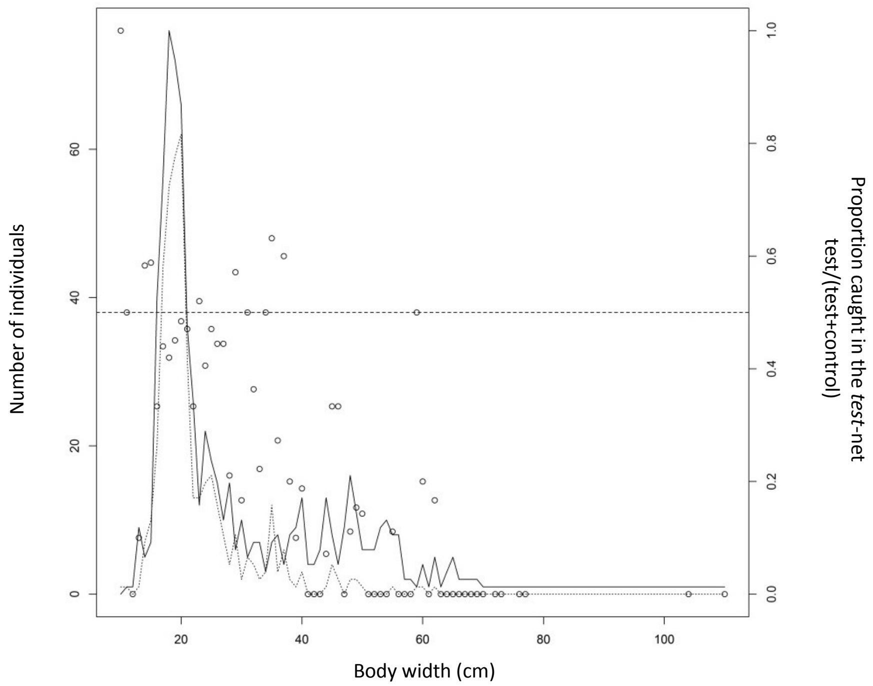
The proportion of rays caught in the *test*-net relative to the control net was defined as: *test*-net catch / (*test*-net catch + *control*-net catch), and is a measure for escape from the net. The relationship between body size and escape was explored using GLMM. The GLMM was applied only to *D. guttata* and *G. micrura*, as insufficient data were available to make a reliable analysis of the three other species. For *D. guttata* a model could be fitted in the size-range between 20 and 72 cm body width using 3-cm-classes. The best fit appeared a second-order model (Table 4; p<0.001), that shows a sharp reduction in catch rate between 20 and 40 cm. Rays larger than 40 cm body width nearly all escaped (Fig. 10b).

For *G. micrura* a model was fitted between 18 and 57 cm body width, using 3-cm-classes. The best model here was linear (Table 4, p=0.00716), showing a steady but limited catch rate reduction over the modelled size-range (Fig. 11b).

Table 4. Coefficient values and significance (P-value) from generalized linear mixed modelling (GLMM) of the proportion (ϕ) of the catch excluded by the *test*-net in relation to body width (S), where $\mathrm{logit}[\phi(S)] = \beta_0 + \beta_1 S + \beta_2 S^2$. β_0 = intercept, β_1 = length, β_2 = length^2

Species	Parameter	Estimate	SE	P-value
Dasyatis guttata	β_1	0.0700	0.0199	<0.001
	β_2	-0.0035	0.0008	<0.001
Gymnura micrura	β_1	-0.0145	0.0054	0.00716

(a)



(b)

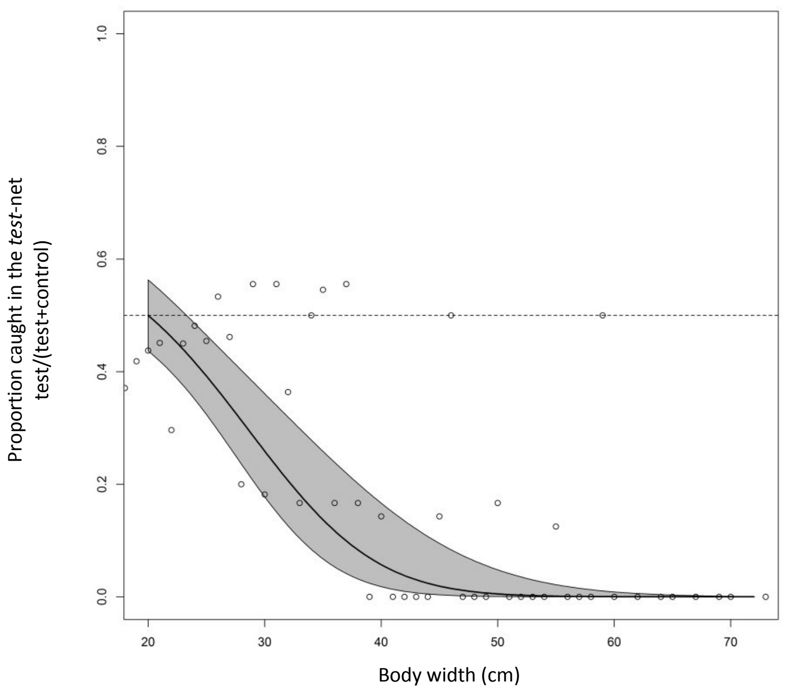
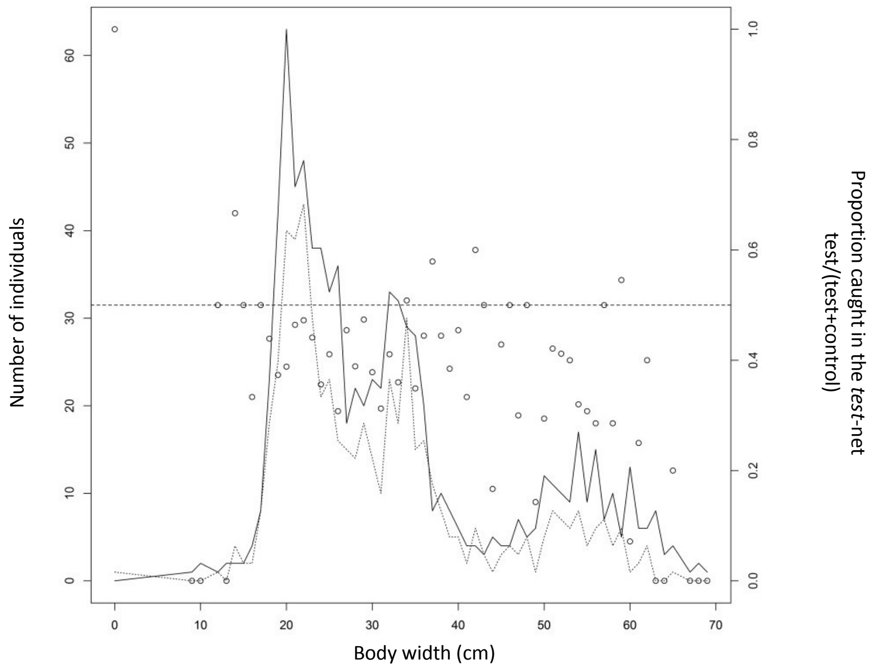


Figure 10. Size distribution (a) and GLMM modelling of size (b) for *Dasyatis guttata.* (a) Pooled length-frequency distributions (solid line: *control*-net; dotted line: *test*-net) and the observed proportion (hollow dots) of the total catch caught in the *test*-net; (b) GLMM modelled proportion of the total catches caught in the *test*-net. Interpretation of (b): A value of 0.5 (dashed line) indicates an even split between the two trawls, whereas a value of 0.2 indicates that 20% of all rays at that body width were caught in the *test*-net and 80% were caught in the *control*-net.

(a)



(b)

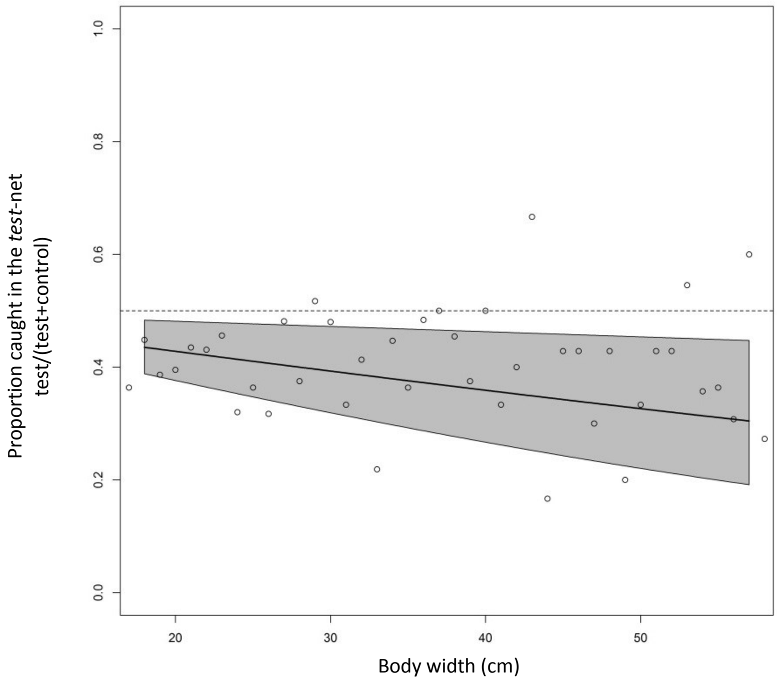


Figure 11. Size distribution (a) and GLMM modelling of size (b) for *Gymnura micrura.* (a) Pooled length-frequency distributions (solid line: *control*-net; dotted line: *test*-net) and the observed proportion (hollow dots) of the total catch caught in the *test*-net; (b) GLMM modelled proportion of the total catches caught in the *test*-net. Interpretation of (b): A value of 0.5 (dashed line) indicates an even split between the two trawls, whereas a value of 0.2 indicates that 20% of all rays at that body width were caught in the *test*-net and 80% were caught in the *control*-net.

4. DISCUSSION

Rays occurred in the study area at any time of the year and were found in the by-catch of both the *test*-net and the *control*-net in each haul conducted during this research. Although catch rate varied considerably among the different sampling days, this does not necessarily reflect temporal patterns in the occurrence of rays, as the study was not designed to assess ray densities. The pattern in Fig. 6 could as well suggest variable spatial occurrence of rays within the study area because all hauls on a sampling day were conducted at a specific part of the study area, at short distance from one another.

Ray by-catch was dominated by two species, *G. micrura* and *D. guttata*, the three other species being far less abundant. Strangely, *Dasyatis americana*, a species that seems abundant at similar depths in neighbouring French-Guyana (Guéguen F., 2000), was not observed. The absence of *Himantura schmardae*, *Aetobatus narinari* and *Manta birostris* was less surprising, as these species are more rare (Léopold, 2005).

Overall, a 36%-reduction in number of rays was observed in the *test*-net compared to the *control*-net. The rays caught in the *test*-net were on average also 21% smaller than the ones occurring in the *control*-net. As such, the *test*-net seemed to exclude larger-sized individuals, suggesting the observed by-catch reductions were the result of escape through TEDs rather than BRDs. BRDs allow small sized fish to escape the trawl, which would theoretically cause a relative size-increase in the *test*-net instead of the observed decrease. We therefore conclude that the BRD was not causing exclusion of rays. Moreover, rays are bottom-dwelling fish and probably have the tendency to stick to the bottom of the trawl rather than swimming towards the BRD, which is located in the upper part of the codend.

Reduction in ray catch rate was most pronounced for *D. geijskesi*, the *test*-net catching 77% less individuals. Although this species appeared quite rare, it was generally large in size. Therefore, *D. geijskesi* escaped through the TED-escape opening in *test*-net at a high rate, only the smaller individuals (mean body width 42 cm; Table 3) being able to pass between the bars of the TED and end up in the *test*-net codend.

By-catch rate of *D. guttata* was reduced by 40%. The mean body width, but especially the size range of individuals caught in the *test*-net was reduced compared to the *control*-net. Looking at GLMM output (Fig. 10b), increasing exclusion occurs for individuals from 20 cm body width and more, rays larger than 40 cm escaping for nearly 100%. Although by-catch of *G. micrura* was reduced by 32%, neither size range nor mean body width was markedly different in the *test*-net. There was, however, a steady increase in exclusion rate with increasing size, as seen in the GLMM output (Fig. 11b). This model shows a very different exclusion-at-size than the effect observed for *D. guttata*. While at a body width of, say, 50 cm nearly all *D. guttata* escape from the trawl, still ca. 35% of the *G. micrura* catch is found in the *test*-net. This probably relates to the fact that the former species is rigid and heavily built compared to the latter, increasing chances for escape than passing between the bars of a TED.

The observed increasing exclusion rate with increasing body size for *D. guttata* and *G. micrura* confirms the escape of larger rays through TEDs. However, for both species, smaller individuals (less than 40 cm) made up the major share of the by-catch (Fig. 10a, 11a). They are not able to escape from the trawls at high rates, which is also seen for *U. microphthalmum*, a small species that showed no exclusion. Thus, although TEDs seem efficient in excluding larger rays, small rays actually make up the bulk of the by-catch, being either small species (*U. microphthalmum*) or young individuals of other species.

At present, no population estimates of rays in the area are available. As such, the impact of the *X. kroyeri* trawling fishery on rays remains unclear. In any case, rays occur quite abundantly where this fishery takes place, and some of the species are globally endangered. TEDs seem to provide best protection for *D. geijskesi,* as mainly relatively large individuals occurred which showed high exclusion rates. This is good news, as the species is endangered, listed 'Near Threatened' on the IUCN Red List of Threatened Species (IUCN, 2013). However, the trawls as they are used now (i.e. the *test*-net), doesn't seem to be appropriate in protecting *D. guttata* and *G. micrura* (both 'Data Deficient'; IUCN, 2013). Mainly smaller individuals of both species seem to occur in the area, which were unable to escape through TEDs. For the same reason, by-catch *U. microphthalmum (*'Least concern'; IUCN, 2013) is not reduced by the use of TEDs. Insufficient data were collected to make any conclusions on *R. bonasus* ('Near threathened';IUCN, 2013).

In summary, this study shows that the selectivity devices currently in use mainly work for large-bodied rays. Further effort could therefor be directed towards avoiding the capture of small-sized individuals. A first step in this direction would be to test alternative selectivity devices. So called 'Nordmore-grids' with fine bar spacing might be interesting in this respect, as they successfully reduced by-catch in a Brazian *X. kroyeri* trawl fishery (Silva et al., 2012).

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