ORIGINAL RESEARCH

Bycatch reduction in shrimp trawl fisheries using a modified net design

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ABSTRACT. The shrimp trawl fishery in northern Peru operates within five nautical miles and presents high bycatch rates. To reduce the impact on marine biodiversity, a new net (MN) was designed and compared against the traditional net (TN) during 27 paired hauls from November 2019 to February 2020 in the area between Los Órganos and Lobitos, Piura. During each haul, two vessels operated simultaneously in the same area, deploying one net each, and total catch, bycatch, and discards were recorded for both nets. The MN showed a reduction of over 35% in bycatch and a 50% decrease in discards compared to the TN. The catch by weight of the target species (*Penaeus californiensis*) and two other commercially important bycatch species (*Diplectrum conceptione* and *Etropus ectenes*) was not significantly affected. Although a decrease in the catch of all taxonomic groups evaluated (fish, crustaceans, mollusks and macroalgae) with the MN was observed, this reduction was not statistically significant for fish. The number of species per taxonomic group (total, fish, crustaceans, mollusks) also decreased with the use of MN, for all taxa evaluated. In summary, the results of this study demonstrate that the implementation of MN, characterized by its different material, exclusion areas and larger mesh sizes compared to TN, allows reduction of the impact of this fishery without affecting the target species catch.

Key words: Fishing gear modification, net selectivity, bottom trawling, Los Órganos, Peru.

Reducción de la captura incidental en la pesca de arrastre de camarón mediante el uso de un diseño de red modificado

RESUMEN. La pesquería de arrastre de camarón en el norte del Perú opera dentro de las cinco millas náuticas y presenta altas tasas de fauna acompañante. Con el fin de reducir el impacto sobre la biodiversidad marina, se diseñó una nueva red (MN) y se comparó con la red tradicional (TN) durante 27 lances pareados realizados entre noviembre de 2019 y febrero de 2020 en la zona comprendida entre Los Órganos y Lobitos, Piura. En cada lance, dos embarcaciones operaron simultáneamente en la misma área, utilizando una red cada una, y se registraron las capturas totales, la fauna acompañante y los descartes para ambas redes. La MN mostró una reducción superior al 35% en la fauna acompañante y una disminución del 50% en los descartes en comparación con la red tradicional

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TN. La captura en peso de la especie objetivo (*Penaeus californiensis*) y de otras dos especies acompañantes de importancia comercial (*Diplectrum conceptione* y *Etropus ectenes*) no se vio significativamente afectada. Aunque se observó una disminución en la captura de todos los grupos taxonómicos evaluados (peces, crustáceos, moluscos y macroalgas) con la MN, esta reducción no fue estadísticamente significativa para los peces. El número de especies por grupo taxonómico (total, peces, crustáceos, moluscos) también disminuyó con el uso de la MN en todos los taxones evaluados. En resumen, los resultados de este estudio demuestran que la implementación de la MN, caracterizada por su material diferente, zonas de exclusión y mallas de mayor tamaño en comparación con la TN, permite reducir el impacto de esta pesquería sin afectar la captura de la especie objetivo.

Palabras clave: Modificación de arte de pesca, selectividad de red, arrastre de fondo, Los Órganos, Perú.

INTRODUCTION

Most commercial fisheries face challenges in reducing bycatch and discards (Rodríguez-Valencia and Cisneros-Mata 2006; Eayrs 2007; FAO 2011; Broadhurst et al. 2012). In this study, we adopted the definition of bycatch proposed by Saila (1983), who describes it as the catch that unintentionally enters the net, meaning it does not correspond to the target species. Depending on various factors, some, all, or none of the bycatch species may be discarded. For the concept of discards, we follow the definition of Alverson et al. (1994), who describes it as the portion of the catch returned to the sea due to economic, legal, or personal reasons. These definitions are particularly relevant to the shrimp fishery, given the high diversity of recorded species (both fauna and flora), the destination of the catch (whether for commercialization or discard), and the skipper's decision to retain certain non-target species.

The ecological impact of bycatch (including discards) lies in the capture of non-target organisms, including turtles, fish, corals, juveniles from target fisheries, non-commercial species, etc. (Cook 2003; Lewison et al. 2004; Eayrs 2007). In 2019, Pérez Roda et al. (2019) determined that annual global marine fisheries discards between 2010-2014 was 9.1 million tons and that approximately 46% of these discards came from catches with bottom trawls. The highest discard rate was 55% (95% CI: 50.0-59.6%) with the use of shrimp trawls (Pérez Roda et al. 2019).

Shrimp and prawns have traditionally been among the most traded aquatic products. In 2020, they ranked as the second most valuable export group (FAO 2022a), which contributes to food security, particularly in developing countries (Gillett 2010). However, shrimp trawling has well-documented impacts on biodiversity, which has led to increased efforts in recent years to reduce bycatch through technological improvements in trawl nets and the implementation of bycatch exclusion devices (Eayrs 2007). In addition to technological improvements, fisheries management strategies to reduce bycatch include the implementation of Bycatch Reduction Devices (BRDs), Turtle Excluder Devices (TEDs), spatial closures, and seasonal restrictions (Eayrs 2007; FAO 2011). Within this management framework, gear modifications are classified as technical measures aimed at improving selectivity and reducing discards while allowing fishing operations to continue (FAO 2011). Unlike spatial or temporal closures, which restrict fishing effort in specific areas or periods, modified nets represent an adaptive mitigation strategy within trawl fisheries management (FAO 2011). For example, the five-year FAO and Global Environment Facility (GEF) project Sustainable Management of Bycatch in Trawl Fisheries in Latin America and the Caribbean (REBYC-II LAC) (2015-2020) promoted the implementation of bycatch management strategies in six Latin American and Caribbean countries. In that context, the REBYC-II LAC project established a target of at least a 20% reduction in bycatch, which served to evaluate the performance of mitigation measures such as modified trawl nets (FAO 2022b).

Despite its global economic importance, shrimp trawling remains an under-researched activity in several countries, including Peru. In northern Peru, shrimp trawl fishing has been operating within the five-mile marine protected zone for several decades (Salazar et al. 2017), despite its prohibition in this area (Supreme Decree No. 012-2001-PE). As a result, this fishery is considered illegal and has been associated with significant environmental impacts, including threats to marine biodiversity (Hooker 2016) and broader ecosystem disruptions (Salazar 2018). Additionally, conflicts between shrimp trawl fishers and other artisanal fishing communities have been reported due to overlapping fishing grounds and competition for resources (Salazar et al. 2015, 2020).

A study conducted between April 2019 and March 2020 in the Cabo Blanco and Máncora area analyzed 300 hauls, identifying 277 species, including fish, mollusks, crustaceans, macroalgae, and other marine organisms (Mendo et al. 2022). The results revealed that the target species, *Penaeus californiensis*, accounted for only 17.8% of the total catch, whereas 82.2% consisted of bycatch and 50.6% was discarded. The most abundant bycatch species were sand perch (*Diplectrum conceptione*, 16% of total catch weight), the macroalga *Caulerpa filiformis* (13%), sole flounder (*Etropus ectenes*, 6.4%), and Pacific drum (*Larimus pacificus*, 5.7%).

Given the high percentage of bycatch and discards in this fishery, a modified trawl net is proposed here to reduce the capture of non-target species and mitigate its impact on marine biodiversity. This net was mainly constructed from polyethylene (PE) and incorporated different net panels, a larger mesh size, a double footrope trawl, and a square mesh window in the lower part of the net. These modifications are designed to enhance catch selectivity by facilitating the escape of non-target organisms. Therefore, this study aimed to evaluate the effectiveness of the modified trawl net in reducing bycatch and its impact on marine biodiversity, providing key insights to mitigate fishing impacts on coastal marine biodiversity in northern Peru.

MATERIALS AND METHODS

Between November 2019 and February 2020, nine fishing trips were conducted within the first 5 nm off the coast between Los Órganos and Lobitos districts (Talara Province, Piura) (Figure 1). Five vessels took part in the study (Table 1). During each trip, two vessels operated simultaneously: one deployed the traditional trawl net (TN) and the other a modified net (MN). This experimental design yielded 27 paired hauls, allowing a direct comparison of the catches obtained with both gear types.

Fishing operations were carried out from 6 pm until 7 am the following day. Catch data and species composition in each haul were collected. Time and speed uniformity of trawling in both vessels was achieved through constant communication with the skippers of the vessels using cell phone. Hauls that did not meet these criteria were excluded from the analysis. In addition, the time of the start and end of each haul and its coordinates for both vessels were recorded using a GARMIN GPS.

Description of traditional and modified trawl nets

A simplified schematic comparison of the TN and MN designs (Figure 2), emphasizing differences in mouth geometry and the incorporation of a double headline in the MN with detailed technical specifications (Figures 3 and 4; Table 2) are provided. Net dimensions and construction details of the TN used by shrimp fishers in northern Peru were obtained during a visit to the net maker who supplies vessels operating in the study area. Although nets used in other shrimp grounds may differ slightly in design, they employed the same material and mesh sizes. The TN featured simple panel cuts, a slightly curved net mouth, and was constructed entirely of polyamide (PA). The mesh size was 31.7 mm throughout the net, except in the codend, where it was reduced to 25.4 mm (Table 2).

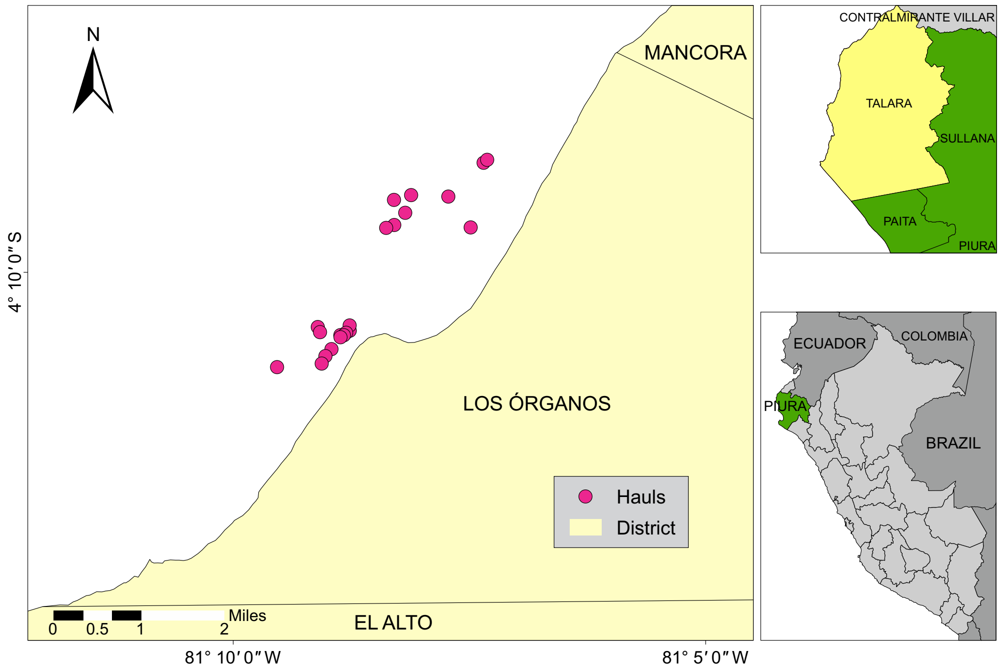

Figure 1. Location of the study area off Los Órganos, Talara, Piura, Peru, indicating paired hauls operations.

Table 1. Principal dimensions and engine power of project vessels.

Vessel	Length (m)	Beam (m)	Depth (m)	Engine make	Hp
‘Milagro de Yave’	8.5	3.1	1.4	NISSAN	100
‘Cristo Viene’	8.5	3.4	1.3	NISSAN	90
‘Señor de los Milagros’	8.7	3.5	1.5	NISSAN	170
‘Jehova es mi Pastor’	9.4	3.3	1.3	NISSAN	150
‘Luz Marina’	7.7	2.8	1.8	NISSAN	90

The MN was designed to improve selectivity by incorporating 60 mm, 50 mm, and 36 mm mesh sizes. Additionally, modifications to the net mouth were made to achieve a more pronounced catenary curvature (Figure 4). The net was constructed primarily from polyethylene (PE) in various sections, including the body, wings, and anterior codend, to reduce its overall weight, which could potentially lead to lower fuel consumption (Villaseñor-Talavera 2012). The codend in the modified net retained the same mesh size and material as the TN. To further enhance selectivity, an additional footrope was incorporated to facilitate the exclusion of certain benthic species, such as soles, starfish, and other bottom-dwelling organisms (INAPESCA 2010). This additional footrope was attached at 50 cm intervals along the connecting lines, increasing in vertical height towards the center of the net (10 cm, 15 cm, 20 cm, with a maximum spacing of 22 cm at the center). In addition, a

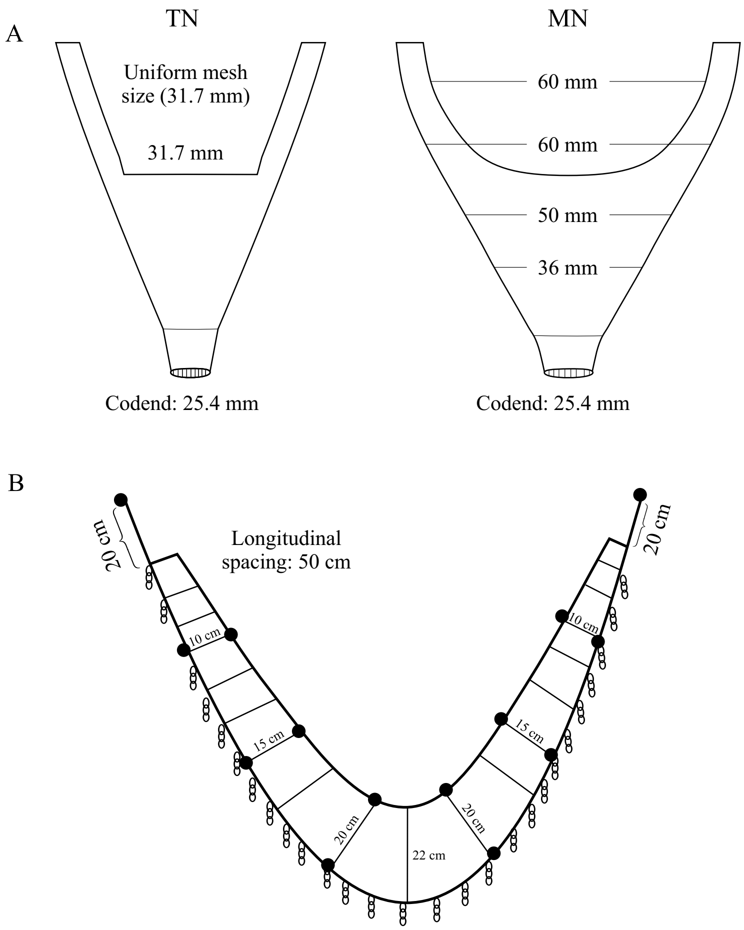

Figure 2. A) Simplified schematic comparison between traditional net (TN) and modified net (MN). B) Detail of double headline configuration of the MN.

square mesh window was added 60 cm from the bottom center of the net mouth to allow the escape of snails and crabs (Eayrs 2007). This square mesh window had a 10 cm mesh size, covering a total area of 1.45 m^2.

It should be emphasized that MN was designed specifically for catching *P. californiensis* (brown shrimp). Although the bycatch included other commercially valuable species, the MN was not a multispecies net: its geometry, mesh sizes and exclusion devices were tailored to maximize shrimp retention and minimize incidental catch. This single-species focus was clearly explained to fishers before the design and testing phase of MN began.

Data collection

Data collection followed the protocol detailed by Mendo et al. (2022). Total catch weight was obtained by subtracting the net weight from the combined weight of the net and catch. Total catch comprises the target species, brown shrimp (*P. californiensis*) and bycatch. In this study, commercial species were those traded by the fishers; among them, *D. conceptione* ('carajito') and *E. ectenes* ('lenguado boca chica') were the main commercial bycatch species.

On board, fishers sorted brown shrimp and commercial species into 0.08 m^3 PVC boxes, which

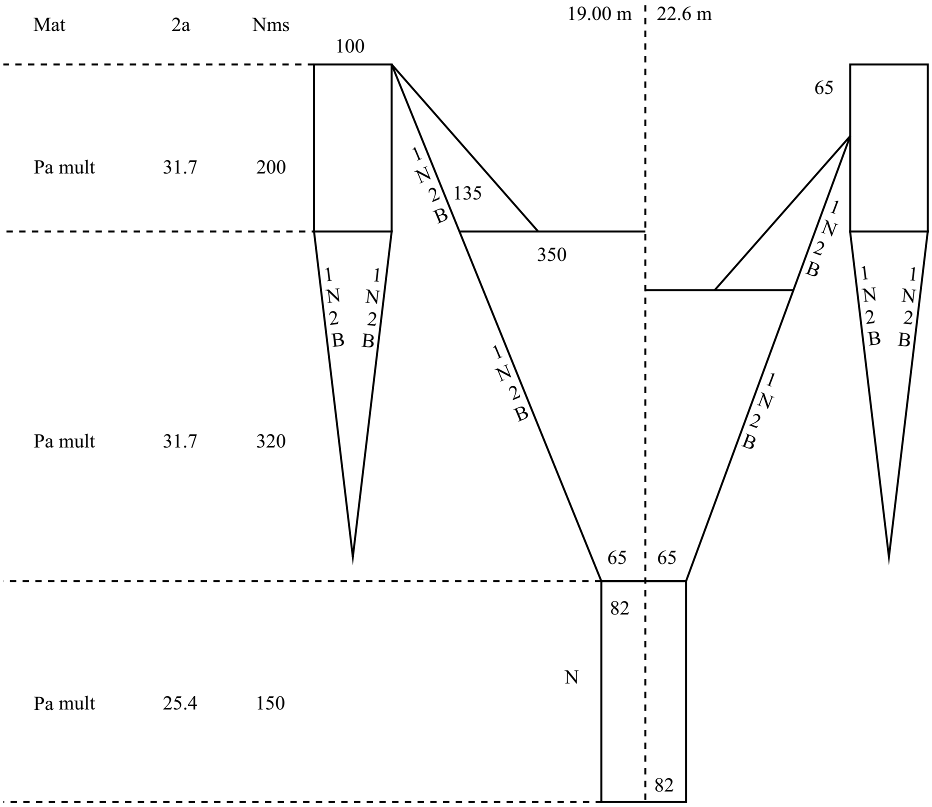

Figure 3. Traditional net used by shrimp fishers in northern Peru.

were weighed by observers following the procedure of Mendo et al. (2022). The remaining catch was classified as discards. For each haul, a subsample of 11 ± 2 kg (± SD) was collected with an 18-l bucket and weighed on a KAMBOR 100 kg digital scale (± 20 g accuracy). On average, this subsample represented 14.0% of the bycatch weight with a SD of ± 8.9 kg. The number and weight of individuals per species or taxonomic group were recorded and extrapolated to total catch.

Total discards (TD) were estimated as:

TD = Total catch – (brown shrimp + commercial bycatch)

Small or hard-to-identify bycatch species were placed in labelled bags and transported to the laboratory in ice-cooled containers with refrigerant gel for later identification and weighing on a digital scale. Species were identified using keys and guides of Chirichigno (1970, 1998), Méndez (1981), Álamo and Valdivieso (1997), IMARPE (2016), Carbajal-Enzian et al. (2018), and Santamaría et al. (2018).

Catch per unit area

Catch per unit area (CPUA, kg km^{-2}) was calculated for each catch component using catch data and the swept area in km^2. The swept area was estimated by multiplying the distance traveled (D; in km), the length of the headrope (L; in km) and the factor X2, the latter being the part of the headrope equivalent to the width of the sector swept by the trawl (Sparre and Venema 1997). The value of X2 = 0.5, proposed by Pauly (1980), was used. The

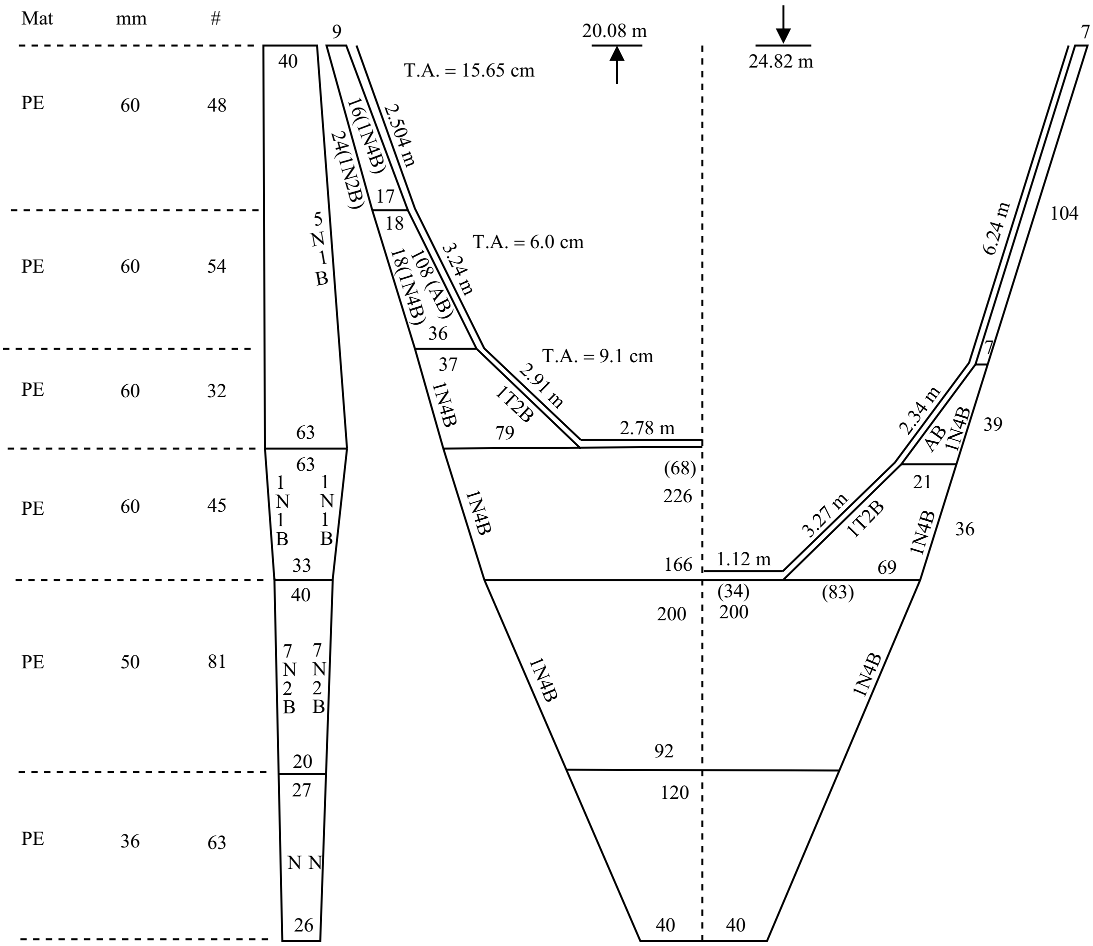

Figure 4. Modified net designed in this study for shrimp trawling fishery.

distance trawled by the vessels was recorded on a GARMIN GPS and processed in the Map Source program. CPUA was computed for main taxonomic groups (fish, crustaceans, mollusks, invertebrates and macroalgae), for *P. californiensis*, for total bycatch, for the principal commercial bycatch species (*D. conceptione* and *E. ectenes*) and for discards.

To compare results between the TN and the MN, the Shapiro-Wilk test ($n < 50$) was applied to assess normality in the distributions (total-catch taxonomic groups, species richness, target-species catch, bycatch, commercial bycatch species and discards). Data sets that met normality were analyzed with paired Student's *t*-tests (mean comparison); non-normal sets were evaluated with paired Wilcoxon tests (median comparison).

CPUA values obtained with both nets for each taxonomic group, bycatch and discards were contrasted using one-tailed (left-side) tests to determine whether CPUA recorded with the MN was significantly lower than that with the TN. In the crustacean comparison, *P. californiensis* was excluded because it is the target species. CPUA for *P. californiensis* (brown shrimp) and for the main commercial bycatch species (*D. conceptione* and *E. ectenes*) was compared with two-tailed tests to assess whether there were significant differences in catches between the two nets.

Table 2. Characteristics of the traditional net (TN) and the modified net (MN).

Parameter	TN	MN
Mesh size		
Wing (mm)	31.7	60.0
Top panel (mm)	31.7	60.0
Tunnel (mm)	31.7	50.0
Extension piece (mm)	31.7	36.0
Codend (mm)	25.4	25.4
Net material	Polyamide (PA)	Wing, top panel, tunnel and extension piece: Polyethylene (PE); codend: Polyamide (PA)
Net modifications	-	Double footrope; exclusion window (10 cm mesh, 1.45 m^2)
Headrope and footrope curvature	Slight curvature	Pronounced curvature

All statistical analyses were performed in R 4.3.1 (R Core Team 2023) within RStudio.

RESULTS AND DISCUSSION

Catch composition by taxonomic group and comparison of the catch obtained between TN and MN

With the MN, the CPUA of the fish group declined by 24%, although the reduction was not significant ($p = 0.235$) (Table 3). The largest decreases were recorded for macroalgae (-66%, $p < 0.010$), mollusks (-46%, $p = 0.011$) and crustaceans other than *P. californiensis* (-37%, $p = 0.013$) (Table 3). Although substantial reductions were observed in absolute CPUA values (Table 3), the proportional composition of the catch by taxonomic group showed minor shifts between TN and MN (Figure 5). This suggested that the modified net reduced overall catch magnitude while producing limited changes in the relative contribution of each taxonomic group.

A similar result was obtained by Padilla-Galindo (2012) in the shrimp trawl fishery in southern Mexico using a prototype net similar to the present investigation, i.e. with a double headrope and a 'False Mesh Window' excluder device (MESD). The only difference is that the latter was placed on top of the extension piece ('antecopo' in Spanish). The fish catch was reduced by 47%, although there were no significant differences when compared with catches obtained by traditional netting. Results presented by Prado (2019) in the artisanal shrimp fishery in Limones Island (Esmeraldas, Ecuador) using only the double netting, show a minimal reduction in fish catch (7%), indicating that the use of double netting mostly reduces the catch of other taxonomic groups such as crustaceans, mollusks and macroalgae as observed in this research (Table 3).

The CPUA of benthic organisms (mollusks, crustaceans and macroalgae) showed a significant reduction with the use of MN (Table 3), since the exclusion panels were in the lower part of the net. Even though there was no significant reduction in CPUA, a higher exclusion of *Prionotus stephanophrys* was observed with the MN compared to the TN in one haul. Specifically, the catch of this

Table 3. Catch per unit area (kg km^{-2}) of the main taxonomic groups of in the bycatch of *Penaeus californiensis* caught with the traditional net (TN) and the modified net (MN).

Taxonomic group	Net type	Mean	Minimum	Maximum	SD	Variation (%)	*p*-value
Fishes	TN	1,627.8	59.4	26,443.4	4,984.1	-24	0.235 ns
	MN	1,239.7	42.4	13,594.8	2,679.0		
Other crustaceans (excluding	TN	144.5	0.0	934.0	183.7	-37	0.013 *
Penaeus californiensis)	MN	91.6	5.2	373.2	90.0		
Mollusks	TN	106.9	0.0	289.9	89.1	-46	0.011 *
	MN	57.6	9.2	229.8	52.8		
Macroalgae	TN	832.7	0.0	4,222.2	1,057.1	-66	0.000 **
	MN	286.6	3.2	1,154.3	329.0		

ns = no significant; * = significant (p < = 0.05); ** = very significant (p < = 0.01).

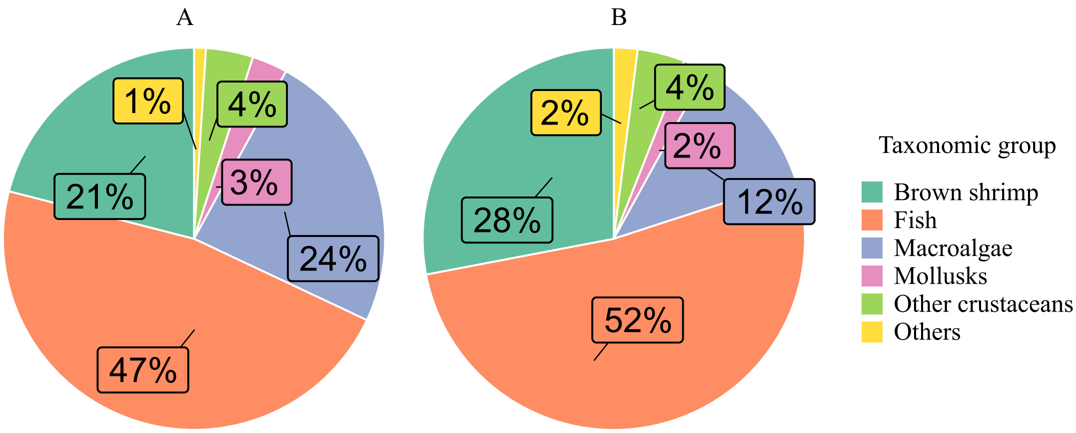

Figure 5. Catch per unit area (CPUA) of brown shrimp (*Penaeus californiensis*) and main taxonomic groups in the catch, recorded in the traditional net (A) and the modified net (B).

species in the TN was 25,792.5 kg km^{-2}, whereas in the MN it was 12,630.4 kg km^{-2} (Figure 6). This reduction may be attributed to the square mesh window (mesh size = 10 cm, area = 1.45 m^2) in the MN, which appears to enhance selectivity for certain abundant species. No statistical analysis was conducted to determine the significance of this difference.

The limited reduction observed in fish CPUA may be related to the position of the square mesh window, which was installed near the mouth of the net and in the lower section. Fish responses to trawl gear have been shown to depend on visual stimulus intensity, hydrodynamic flow cues and individual swimming performance relative to towing speed (Kim and Wardle 2005). Therefore, the location of the escape opening within the net structure may influence the likelihood of contact and escape, potentially explaining the lower exclusion observed for fishes compared to benthic-associated groups. Padil-

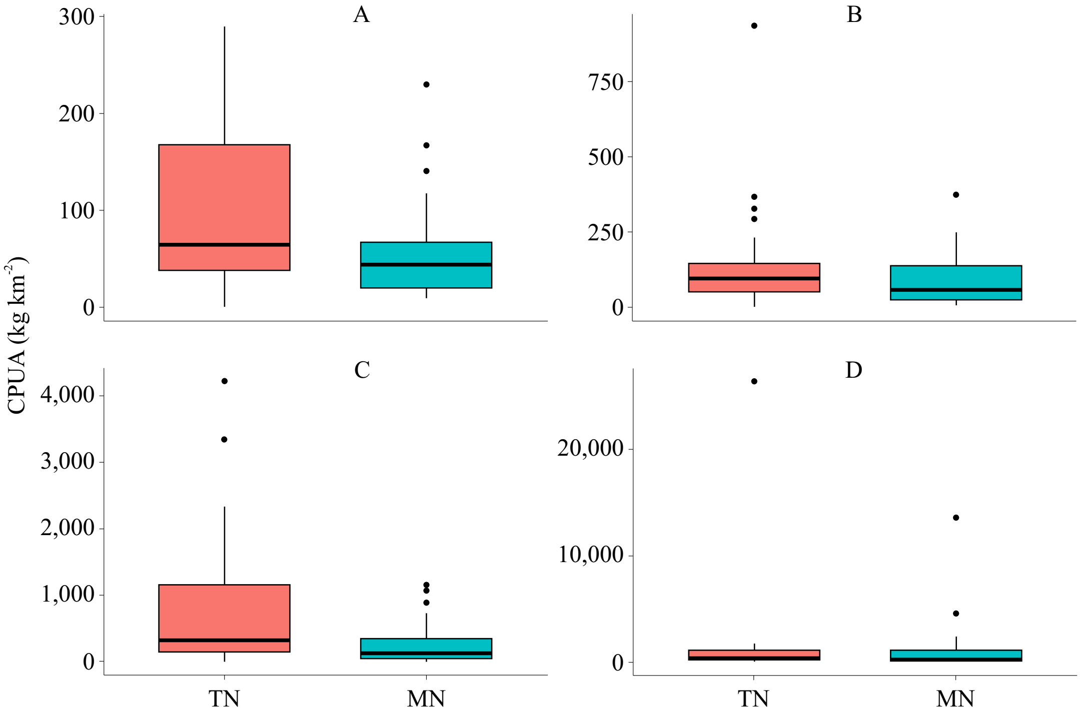

Figure 6. Catch per unit area (CPUA) of bycatch from *Penaeus californiensis* trawling using traditional net (TN) and modified net (MN). A) Mollusks. B) Other crustaceans. C) Macroalgae. D) Fishes.

la-Galindo (2012) reports a reduction between 36% and 42% for invertebrates with the use of a double footrope (DRI). Medina-Carrillo et al. (2012) obtained better results, achieving a reduction of 71% (DR 'double footrope' + DET). The inclusion of an additional footrope in MN had a significant influence on the reduction of this taxonomic group.

Macroalgae were the taxonomic group with the highest exclusion rate (66%), primarily represented by *C. filiformis*, the most abundant macroalgae recorded in the catches. This species of macroalgae serves as a refuge for the seahorse (*Hippocampus ingens*), a species classified as threatened under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (IMARPE 2007). However, the present study quantified only the biomass retained on deck and did not evaluate the fate of macroalgae during the trawling process. It is therefore possible that macroalgae were mechanically detached by the modified net (MN) and subsequently expelled through the square mesh window (10 cm mesh size), rather than reflecting an actual decrease in their abundance in the fishing area. Consequently, the observed reduction should be interpreted cautiously, as it may represent differences in retention efficiency rather than a direct ecological effect.

According to previous studies on bycatch composition (for example, Flórez-Leiva 2007; INAPESCA-FAO 2021), macroalgae are often not included in bycatch reports due to their low biomass. In contrast, the present study found that macroalgae, particularly *C. filiformis,* represented a significant proportion of the total catch, highlighting the importance of their reduction when using the MN.

Modifications made to the net were not aimed at excluding large species. The capture of an individual olive Ridley (*Lepidochelys olivacea*) 'Olive Ridley turtle', classified as vulnerable (VU) as reported in the Categories and Criteria of the IUCN Red List, could not be avoided; however, it should be noted that the species was released alive. In this sense, it is of great importance for future studies in this fishery to use the TED (Turtle Excluder Device), which is a grid that separates larger organisms such as sea turtles, sharks, rays, jellyfish, some large fish or objects that enter the net, causing them to exit through an opening built into the net at the base of the grid (Eayrs 2007; Alió et al. 2009a).

This study does not assess the survival of discarded species, namely those returned to the sea after being caught, nor does it provide information on organisms that enter the net and are subsequently excluded due to modifications applied to the trawl net. When analyzing the total catch on deck, it was observed that invertebrates, mainly crabs, showed signs of vitality, while most fish exhibited poor mobility or were dead. However, no information was obtained regarding the survival of species that entered the net and were later excluded at sea. In this context, it is essential to emphasize the need for further research to address this issue. As Suuronen (2005) points out, several studies have shown that physical damage sustained during the catch and release process can lead to fish mortality. Therefore, the assessment of escapement mortality should be considered a key component in the development of selective fishing gear.

Catch composition by fishers' use and comparison of the catch obtained between TN and MN

The proportion of discards recorded with the TN (64%) (Figure 7) differs from previous studies: Inga et al. (2010) reported 33% in Máncora, whereas Ordinola et al. (2008) recorded 95% in Caleta La Cruz. These variations are due to differences in fishing zones, market demand, and local practices. In fact, Ordinola et al. (2008) noted that *Larimus pacificus* was considered commercial in Máncora, while *D. conceptione* ('carajito') was discarded in La Cruz. It is likely that these species have gained greater commercial value over time, reflecting changes in market preferences and the utilization of fishery resources.

Results for the total commercial catch (*Penaeus californiensis* as the target species, plus all commercially valuable bycatch species), with averages of 1,241.7 kg km^{-2} for TN and 1,268.2 kg km^{-2} for MN (Table 4). This difference was not statistically significant ($p = 0.269$). Similarly, the paired comparison for *Penaeus californiensis* yielded a p-value of 0.126, indicating that the use of the MN does not significantly affect the catch of the target species. This can be explained by the behavior of the shrimp when contacting the footrope: they perform tail-flips that allow them to ascend a few meters in the water column, and once inside the co-

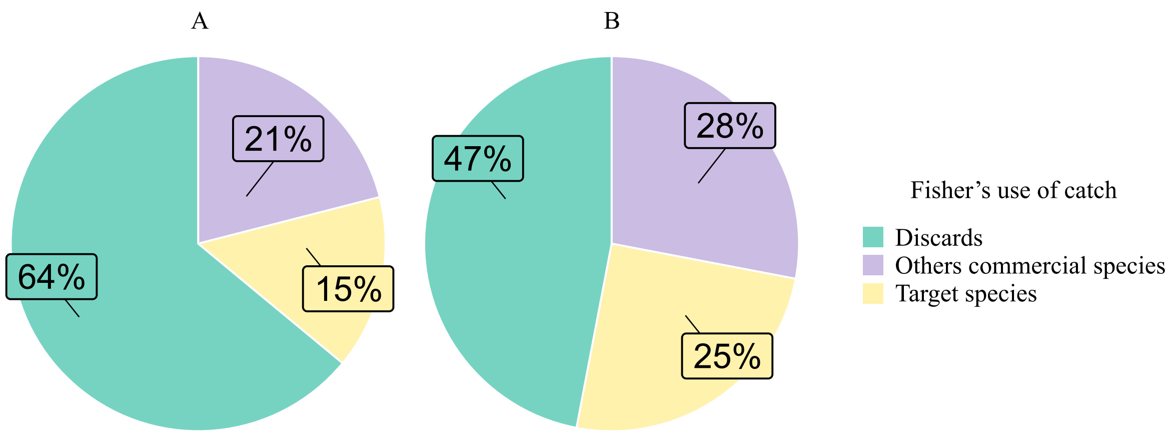

Figure 7. Catch composition according to fisher's use. A) Traditional net. B) Modified net.

Table 4. Catch per unit area (kg km^{-2}) of main catch components obtained with the traditional net (TN) and the modified net (MN).

Parameter	Net type	Mean	Minimum	Maximum	SD	Variation (%)	*p*-value
Penaeus californiensis	TN	736.7	78.8	1,500.1	355.5	-9	0.126 ns
	MN	670.5	190.4	1,550.7	337.7		
Commercial catch total	TN	1,241.7	342.5	2,074.9	444.3	-2	0.269 ns
	MN	1,268.2	383.2	4,786.4	967.2		
Bycatch	TN	2,752.4	238.0	26,625.4	4,896.9	-38	0.001 *
	MN	1,713.1	186.0	13,826.7	2,630.4		
Discards	TN	2,247.4	198.2	25,792.5	4,831.0	-50	0.000 *
	MN	1,115.4	124.3	13,633.9	2,531.0		

ns = no significant; * = very significant (p < = 0.01).

dend, their escape capacity is limited (Eayrs 2007; Alió et al. 2009b).

In contrast, the MN reduced total bycatch by 38% and discards by 50% ($p < 0.01$ in both cases), confirming the effectiveness of the double lower headline and the square mesh window in excluding benthic organisms. However, Alió et al. (2009a) warned that incorrect installation of the headline excluder particularly when both ends are tied at the same point can hinder its efficiency by preventing proper separation during towing, thereby reducing its ability to exclude non-target species.

The low species selectivity observed with the traditional net could be attributed to the uniform mesh size used throughout most of the net (31.7 mm), except in the codend (25.4 mm). In contrast, the MN incorporates larger meshes in the upper panel, body, and anterior sections, which improves selectivity by favoring the retention of larger organisms and allowing smaller individuals to escape.

Villaseñor-Talavera (2012) highlighted that polyamide nets with twisted twine, such as the TN, tend to be heavier and generate greater resistance during towing. The use of polyethylene (PE) in the MN, a lighter material, reduces the total weight of the gear, consequently lowering fuel consumption and bottom impact. Although this aspect was not a primary objective of the present study, PE nets have been associated with lower towing forces, fuel savings, and reduced machinery wear (INAPESCA 2010; Villaseñor-Talavera 2012). Within the framework of the REBYC-II LAC project (Colombia), a PE net prototype achieved a 24% reduction in fuel consumption and a significant decrease in CO_2 emissions (INVEMAR 2021). Additionally, the reduction in retained bycatch when using escape devices may decrease the total load during towing, which could potentially contribute to operational efficiency; however, this aspect was not directly evaluated in the present study.

Although mean values were higher with the MN, differences were not statistically significant ($p = 0.2514$ for *D. conceptione*; $p = 0.5379$ for *E. ectenes*) (Table 5). This result was expected, as both species are finfish, and it is consistent with the limited reduction observed for this taxonomic group. However, the lower double headline was designed to reduce the capture of flatfish (*E. ectenes*), and such exclusion was not evident, in contrast to the findings of Padilla-Galindo (2012) and INAPESCA (2010).

From an economic perspective, the MN (mainly made of PE) costs approximately 8% less than the polyamide (PA) TN (Mendo et al. 2020), and the initial investment for the TN represents less than 3% of a vessel's gross annual income (James et al. 2023). The combination of stable target catch,

Table 5. Catch per unit area (kg km^{-2}) of main commercial bycatch species caught with the traditional net (TN) and the modified net (MN).

Parameter	Net type	Mean	Minimum	Maximum	SD	Variation (%)	*p*-value
Diplectrum conceptione	TN	69.2	0.0	463.0	142.1	55	0.2514 ns
	MN	107.1	0.0	725.3	209.6		
Etropus ectenes	TN	259.8	0.0	1,523.3	383.6	41	0.5379 ns
	MN	365.1	0.0	3,898.5	841.4		

ns = no significant.

maintenance of total commercial catch (particularly *D. conceptione* and *E. ectenes*), and reduced material costs suggests that adopting the MN would not pose an economic barrier and could enhance fleet profitability. Nevertheless, future studies should examine size, maturity, and other biological parameters of the commercial bycatch species to fully assess the net's impact.

Reduction in species number between TN and MN

The total number of species, as well as the number of species per taxonomic group, was significantly lower ($p < 0.01$) with MN compared to TN (Table 6). This indicates that MN was more effective in excluding a greater variety of species. However, it is important to note that while no significant reduction in fish catch was observed in terms of CPUA, there was a significant reduction in the number of fish species captured. This suggests that the modified net does not necessarily reduce the total biomass of fish caught, but it does lead to a decrease in species diversity, which is also a key indicator of selectivity.

Overall, findings of this study indicate that modifications to the trawl net can effectively reduce bycatch and discards. However, additional management strategies are necessary to enhance their impact and ensure the sustainability of the fishery. The study conducted by Mendo et al. (2023) between April 2019 and March 2020 in the Cabo Blanco and Máncora area analyzed 300 hauls, revealing that the bycatch-to-shrimp ratio averaged 5.7:1, with peak values of 10.5:1 in May and 12:1 in December 2019. These findings highlight the need for temporary or spatial fishery closures during periods of high bycatch as an effective measure to mitigate its impact and promote sustainability. This approach has been widely recommended in the scientific literature (Foster and Arreguín-Sánchez 2013) and successfully implemented in fisheries management initiatives, such as the REBYC-II LAC project in Colombia, where targeted closures were established to reduce fishing effort in specific areas and time periods (INVEMAR 2021). If such closures are combined with the use of excluders and modifications to trawl nets, as demonstrated in this study, significant progress can be made toward a more sustainable shrimp fishery, aligning with the objectives of the FAO Code of Conduct for Responsible Fisheries. Finally, Hilborn et al. (2023) highlight that environmental impacts of trawling can be significantly mitigated through improved management strategies, including gear modifications and spatial regulations. While trawling has environmental impacts, they are comparatively lower than those of livestock and aquaculture in terms of water use and antibiotic dependence. Therefore, although banning bottom trawling could reduce its direct effects on marine ecosystems, it might lead to greater overall environmental impacts if replaced by more resource-intensive land-based or aquaculture production systems (Hilborn et al. 2023).

Table 6. Comparison of the number of species of the accompanying fauna of *Penaeus californiesis* classified by taxonomic group with the use of the traditional net (TN) and modified net (MN).

Taxonomic group	Net type	Mean	SD	*p*-value
Total	TN	32.1	9.03	0.000 *
	MN	25.7	4.43	
Fishes	TN	15.9	5.40	0.004 *
	MN	13.6	3.00	
Crustaceans	TN	7.0	2.90	0.004 *
	MN	5.5	1.80	
Mollusks	TN	3.7	2.30	0.003 *
	MN	2.2	0.80	

* = very significant (p < = 0.01).

CONCLUSIONS

The present study has demonstrated that the implementation of a modified net (MN) in the shrimp trawl fishery in Piura (in front of Los Órganos) is a viable alternative to reduce bycatch and discards, without significantly affecting the target catch (*P. californiensis*). With the use of the MN, a significant reduction of 38% in bycatch and 50% in discards was observed compared to the traditional net (TN), suggesting an improvement in the selectivity of the modified net. It must be emphasized that the fishery operates inside Peru's 5-mn zone, where trawling is banned and, more recently, within a Marine Protected Area; it is therefore illegal. While adopting the MN is a technological advance, it does not resolve the fleet's legal status and should be viewed as a first step that must be reinforced through formalization, effective enforcement and dialogue with coastal communities.

Although the percentage reduction in bycatch is substantial, the absolute volume remains high when broken down by taxonomic groups, indicating that gear selectivity can still be improved. Because the study was conducted in a single area off the Piura coast, trials should be replicated in other fishing grounds to validate the MN's effectiveness. Future studies could consider applying standardized testing protocols for bycatch reduction devices (BRDs), such as those described by Eayrs (2012), which provide guidance on experimental design and evaluation procedures. In addition, technical manuals developed for turtle excluder devices (TEDs), such as Mitchell et al. (1995), offer practical recommendations on the design and performance of selective devices in shrimp trawl fisheries. Aligning future trials with these internationally recognized guidelines could strengthen methodological robustness and facilitate comparisons among studies.

Nevertheless, only an integrated approach that combines technological innovation with legal regularization, participatory monitoring and effective enforcement will secure the long-term sustainability of this fishery.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Ethical statement

The authors declare that no experiments involving live animals or humans were conducted.

Author contributions

Alejandra Travezaño Ambrosio: conceptualization; methodology; investigation; data curation; formal analysis; visualization; writing-original draft. Jaime Mendo: conceptualization; project administration; supervision; funding acquisition; writing-review and editing. Saúl Sarmiento-Nafate: methodology; investigation (net design); writing-review and editing. Jesus Villalobos Toledo: methodology; investigation (net design); writing-review and editing. Renato Gozzer-Wuest: writing- review and editing. Jorge Grillo-Núñez: writing-review and editing. Mark James: writing-review and editing. Iván Gomez-Oré: investigation; data curation; resources. Ruggeri Delgado: investigation. Jhenifer Fernández: investigation. Karla Loza-Choque: investigation. Carlos Fuentevilla: writing-review and editing. Tania Mendo: conceptualization; formal analysis; supervision; writing-review and editing.

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