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RESEARCH ARTICLE

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New codend designs to improve the size selectivity of fyke net for narrow-clawed crayfish (*Pontastacus leptodactylus*)

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Abstract – The narrow-clawed crayfish (*Pontastacus leptodactylus*) is one of the most ecologically and economically important freshwater species in Turkey. However, the harvest of this species has declined from 7937 t in 1984 to 696 t in 2019. One of primary reasons for this decrease in stock is the use of fishing gears with poor size selectivity. In this study, new codend designs were investigated to improve the size selectivity of fyke nets for *P. leptodactylus*. Seven codends of three different designs were tested: (1) a commercially used standard codend with 34 mm mesh size (*Com34*); (2) sorting grids with 20 (*SG20*), 25 (*SG25*) and 30 mm (*SG30*) bar spacing attached to the last circle of the net; and (3) a stiff rigged net, the last part of the fyke nets (codend) with 34 (*SRN34*), 42 (*SRN42*) and 50 mm (*SRN50*) mesh size. The average length at 50% retention probability (L_{50}) and selection range (*SR*) (L_{75}–L_{25}) values of *Com34* were 9.4 cm and 3.1 cm, respectively. For the *SG20*, *SG25* and *SG30* grids, the L_{50} values were 11.3 cm, 11.6 cm and 12.0 cm, while the *SR* values were 1.4 cm, 1.3 cm and 0.6 cm, respectively. For the *SRN34*, *SRN42* and *SRN50* codends, the L_{50} values were 10.9 cm, 11.6 cm and 11.6 cm, while the *SR* values were 2.1 cm, 2.1cm and 1.1 cm, respectively. Overall, the commercial codend resulted in lower L_{50} values when the minimum conservation reference length of 10 cm was considered. However, all tested new codend designs showed improved selectivity compared with the standard, with optimum results obtained with *SG20*. *SG20* grid decreased discarding by 15.7% compared to the classic commercial fyke net; thus, this is a very important result for the sustainability of natural *P. leptodactylus* stocks.

Keywords: *Pontastacus leptodactylus* / fyke net / size selectivity / sorting grid / stiff rigged net

1 Introduction

Narrow-clawed crayfish (*Pontastacus leptodactylus* Eschscholtz, 1823) is globally distributed in lentic and lotic ecosystems (Albertson and Daniels, 2018; Momot et al., 1978; Taylor et al., 1996). They serve as ecosystem engineers, especially for low-phytoplankton lakes (Momot et al., 1978). The global freshwater crayfish production from fishing was 487 t in 1950, and it increased to 11654 t in 2019 (FAO, 2021). However, catches have shown a significant downward trend in Turkey over the last decades. The total production in Turkey was 3885 t in 1977 and peaked at 7937 t in 1984, before declining over the following years (a minimum of 320 t in 1991) and reaching 696 t in 2019 (FAO, 2021). The most important reason for this severe decline in production amounts is the crayfish plague (caused by the fungal oomycete *Aphanomyces astaci*), which was first reported in Çivril Lake in 1984 in Turkey, and it then spread to other lakes (Timur et al., 2010). Most native European freshwater populations have collapsed due to *A. astaci* (Souty-Grosset et al., 2006; Kokko et al., 2012), whereas Turkey's freshwater crayfish populations have not collapsed, though they have been severely devastated. Commercial fishing was subsequently banned to protect the stocks. In addition to disease, overfishing, water pollution and agricultural irrigation are the main reasons for the decrease in Turkish crayfish stocks (Harlioğlu and Harlioğlu, 2009; Rahe and Soylu, 1989; Köksal, 1988).

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Fyke net, a type of trap, has been used in marine and inland waters worldwide (Bolat et al., 2010; Gabriel et al., 2005). These nets are cylindrical or cone-shaped mounted on rings or other rigid structures (FAO, 2020). The fyke net is the only fishing gear used for crayfish fishery in Turkey. Fishermen prefer these nets owing to certain advantages, such as relatively high catching efficiency, low cost, light weight and the fact that they do not take up much storage space. Crayfish enter the fyke net instinctively to find shelter or by encountering the guiding nets during their movements on the sea floor. Boats ranging in length from ~7 to 9 m are used for crayfish fishing in Eğirdir Lake, and fishing generally occurs in relatively deep parts of the lake (6–10 m). Use of bait while fishing is prohibited by law (Anonymous, 2020).

The ecosystem approach to fisheries (*EAF*) is defined by Dimech et al. (2014) as 'a management planning process rooted in the principles of sustainable development and using risk assessment methodologies'. However, fisheries are not managed in the scope of *EAF* in Turkey. There is only one sample plan for Gökova Bay (the eastern Aegean Sea, southwest of Anatolia, Turkey) for small-scale fisheries (Ünal et al., 2019) that is supported by *FAO*. Most fishing activities are not selective enough, thereby generating bycatch and discards (Garcia et al., 2003). This is one of the negative effects of fisheries on the ecosystem that must be addressed by the *EAF*. The landed bycatch ratio of *P. leptodactylus* was reported to be 77.2% in Turkey, and 40.7% of the bycatch comprised of small-sized crayfish (Anonymous, 2022). A high bycatch ratio of *P. leptodactylus* stems from the use of poorly selective gear. Both the *FAO* and European Commission encourage the use of more selective fishing practices to reduce or eliminate bycatch and improve sustainability (Pérez Roda et al., 2019; Suárez et al., 2021). The basic principle of sustainability is that species are caught only after they spawn at least once. Species begin to reproduce after reaching a certain age and size. Therefore, size selectivity is of prime importance (Armstrong et al., 1990; McLennan, 1992). In this context, it is necessary to be well aware of both the size at maturation of the target species and the selectivity characteristics of the gears used in fishing. In studies on the reproductive biology of *P. leptodactylus*, the L_{50}, defined as the length at 50% retention probability, was 9.79 cm total length (*TL*) for females in Eğirdir Lake (Balik et al., 2005) and 9.04 cm *TL* for those in Hirfanlı Dam (Cilbiz, 2020). Considering the reported L_{50} sizes, it can be said that the minimum landing size (*MLS*) applied as 10 cm *TL* is compatible with the biology of the species. To date, few studies have been conducted on the selectivity of fyke nets in *P. leptodactylus* fishing (Bolat et al., 2010; Bolat and Uçgun, 2019). In these studies, which used the *SELECT* (Share Each Length class Catch Total) method, the L_{50} values for 34-mm conventional codends were below the considered *MLS* of 10 cm.

Eğirdir Lake (Southern-Anatolia) is the second-largest freshwater resource in Turkey, with a surface area of 457 km^2 (Sener et al., 2019), and is also the most productive fishing groud for *P. leptodactylus* (with an officially recorded total annual harvest of 1233 t in 2020) in Turkey (Turkstat, 2022). Commercial fishing activities are carried out by 11 fishery cooperatives in five fishing areas of the lake.

Generally, fyke nets rigged with 34 mm diamond mesh size are used in Turkey crayfish fisheries. Commercial fyke nets have low selectivity due to codend meshes that close while fishing. In order to prevent the codend from closing and improve selectivity, meshes can be stiffly rigged or a rigid sorting grid can be used in the fyke net fishery. This study aimed to improve the conventional fyke net size selectivity for *P. leptodactylus* using sorting grids with 20, 25 and 30 mm bar spacing and stiff rigged nets with codends of 34, 42 and 54 mm mesh size. A covered codend technique (Wileman et al., 1996) was used for determining the length selectivity of codends seasonally.

2 Material and methods

2.1 Data collecting process

The study was conducted between April 2017 and January 2018 in Eğirdir Lake. The nets were deployed in the morning and were hauled up and controlled after two days (soak time: approximately 48 h). Mean fishing depth was 7.4 m. A 4.55 m LAO fibre boat with a 30 hp outboard engine was used in the experiments.

2.2 Description of the grid, grid sections and codends

In the design of the fyke nets to be used in this experiment, the structural characteristics of commercial nets were followed to the extent possible. Technical specifications are shown in Figure 1. The nets had two sections (one set); each section had a 'D'-shaped hoop (Fig. 1, first hoop in red) and four cylindrical (25 cm diameter) iron frames with two funnels. The iron frames were 3 mm thick.

Seven codends of the following three designs were tested (Fig. 1).

2.2.1 Commercial codend (Com34)

No structural changes (in terms of end of the codend and mesh size) were made in commercial fyke nets with a nominal diamond mesh size of 34 mm (Fig. 1A).

2.2.2 Stiff rigged net (SRN)

Owing to the structure of the net, codend meshes close during fishing. To prevent the closure of codend meshes and improve their selectivity, 34 (*SRN34*), 42 (*SRN42*) and 50 mm (*SRN50*) mesh sizes were stiffly rigged on the last circle (3 mm thickness and 20 cm diameter) with 0.7 hanging ratio (E) (this ratio is a measure of the maximum opening of meshes) (Fig. 1B). All codends, including *Com34*, were made of the same material (polyamide, *PA*), with 210D/12 (denier/ply) no twine thickness.

The codends' mesh sizes were measured using a calliper with a 4 kg weight vertically tied to the stationary jaw of the ruler, following the method of Fonteyne et al. (2007). Both *Com34* and *SRN34* had the same mesh size (+SD) of 34.7 ± 0.08 mm, while *SRN42* and *SRN54* had mesh sizes of 42.6 ± 0.06 and 54.5 ± 0.04 mm, respectively.

2.2.3 Sorting grid (SG)

Initially, bar spacing was determined based on the *TL*–carapace width relationship using the morphometry data retrieved from the institutional archive of Eğirdir Fisheries Research Institute. The carapace widths of *P. leptodactylus* in the female, male and combined sex groups of 10 cm *TL* (*MLS*) were

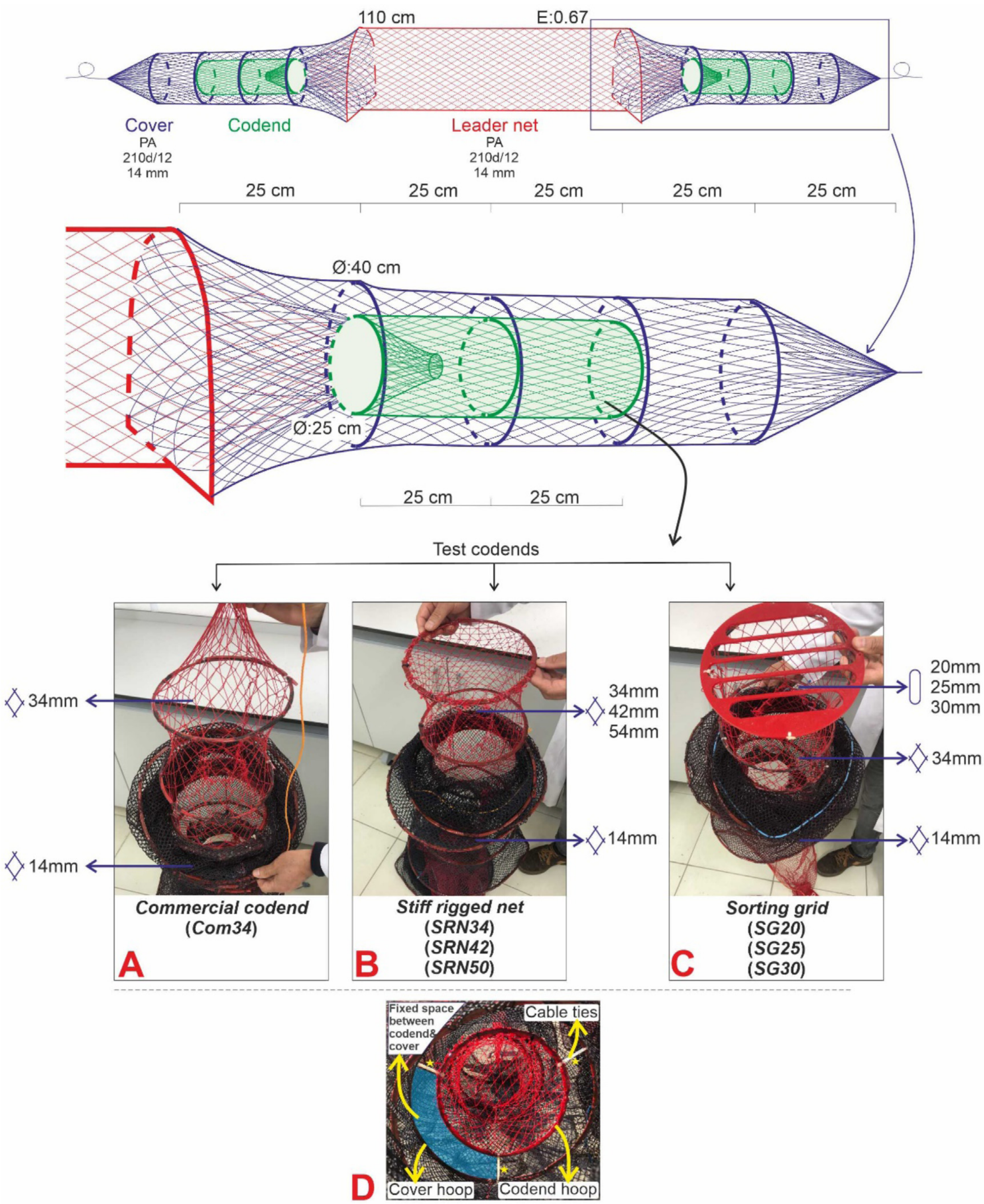

Fig. 1. Technical properties of experimental fyke nets and test codends used in the study A. Commercial codend (*Com34*). B. Stiff rigged net (*SRN34, SRN42, SRN54*). C. Sorting grid (*SG20, SG25, SG30*). D. The process of preventing masking effect.

calculated as 24.8, 25.9 and 25.4 mm, respectively. Therefore, 20 (*SG20*), 25 (*SG25*) and 30 mm (*SG30*) bar spacing selectivity parameters were chosen for investigation (Fig. 1C). Both grid frames and bars were made from Poly(methyl methacrylate) (*PMMA*) and fabricated via laser cutting. They had a diameter of 25 cm and the frames were round and 5 mm thick. In each grid, three bars were randomly selected and measured to compare the homogeneity of the bar spacing. A precision digital calliper was used to measure the grid bar spacings, which revealed mean spacing values (±SD) of 20.3 ± 0.02, 25.2 ± 0.03 and 30.2 ± 0.05 mm for *SG20*, *SG25* and *SG30*, respectively. No significant differences were found between the bar spacings by ANOVA (*SG20*, $F = 0.41$ and $p > 0.05$; *SG25*, $F = 0.50$ and $p > 0.05$; *SG30*, $F = 0.51$ and $p > 0.05$).

Individual crayfish that were small enough could escape by passing through the mesh and grid bars, while larger individuals were retained in the codends. An ad-hoc covered codend was designed according to Wileman et al. (1996), with specifications as shown in Figure 1. The cover had three circles and was attached to the middle of the third and fourth circle of the net. To prevent masking, the cover circle had a diameter 1.5 times larger (37.5 cm) than that of the fyke net hoops. The

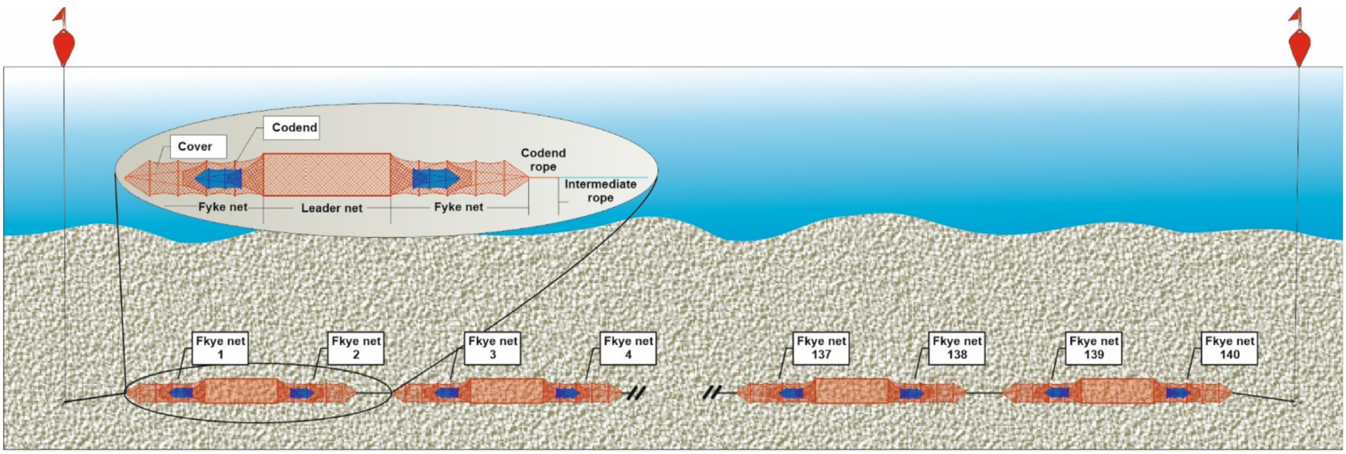

Fig. 2. General view of combined experimental fyke nets on the lake bottom.

codend circles were fixed at the centre of the cover circles using cable ties (Fig. 1D). The covers were made of *PA*, with 210d/12 (denier/ply) no twine thickness and 14 mm mesh size. These covers were 80 cm in length, with 110 meshes on their circumferences, and were rigged in the third circle of the nets. The covers were placed between the second and third circles of the experimental fyke net to fix the cover net.

A total of 140 fyke nets with 20 sets (40 codends and covers) for each test codend were used. These were randomly connected to each other using a 5-mm thick and 5-mm long polypropylene rope. A general view of the combined experimental fyke nets on the bottom is shown in Figure 2. The experiments were performed seasonally during 2017 and 2018, and carried out twice in spring, once in summer, twice in fall and twice in winter (seven total operations).

2.3 Size selectivity analysis

After lifting the fyke nets, the catches for each codend were emptied separately. Then, crayfish were collected, while other specimens were released back into the water. The *TL* of all crayfish was measured to the nearest 0.01 cm using a digital calliper. *TL* was calculated as the sum of carapace length and abdomen length. The applied experimental design (Fig. 1) for the codends enabled the analysis of the collected catch data, where individuals were retained either by the codend cover or the codend itself, as binominal data. These data were used to estimate the size selectivity of the codends (i.e. length-dependent retention probability). Size selectivity is expected to vary between hauls with the same codend (Fryer, 1991). The probability of finding a crayfish of length l in a codend in haul j is expressed by the function $r_j(l)$. The purpose of the analysis was to estimate the values of this function for all relevant sizes of crayfish (Herrmann et al., 2012). Each codend was analysed separately using the method described in the Appendix A.

2.4 Inferring the differences in size selectivity between codends

To determine the differences in retention probabilities, the following generic delta curve ($\Delta r(l)$) was used:

$$\Delta r(l) = r_{test}(l) - r_{baseline}(l) \tag{1}$$

where on a case-by-case basis, $r_{test}(l)$ is the retention probability value of a specific codend with a modified design and $r_{baseline}(l)$ is the retention probability value of the baseline design in each pairwise comparison. Further information about retention probabilities can be found in the Appendix A.

2.5 Estimation of fishing efficiency indicators

To investigate how applying the considered codends would affect the capture pattern in the fisheries, values were estimated for three exploitation pattern indicators, nP^-, nP^+ and *nDiscard*. These performance indicators are often used in fishing gear size selectivity studies to supplement assessments based solely on selectivity curves (Brčić et al., 2018; Cheng et al., 2019; Kalogirou et al., 2019; Melli et al., 2020; Santos et al., 2016; Sala et al., 2016). For more details on the performance indicators considered, refer to the Appendix A.

All analyses (size selectivity, retention probability and efficiency indicators) were conducted using the *SELNET* (SELection in trawl NETting) software v.10 (Herrmann et al., 2012). *SELNET* can acquire and analyse size selectivity and catch data for towed fishing gears, both at the haul level and for a group of hauls (Wienbeck et al., 2011). Plots were made by R Core Team, 2021 (v. 4.0.3) on an RStudio Team. 2021. (v. 1.4.1106) software using the 'ggplot2 (v.3.3.3)' package (Wickham, 2016).

2.6 Calculating the catch per unit of fishing effort (CPUE)

CPUE values were computed according to FAO (2018) using the formula (2). A fisherman and station were taken as a basis for determining the nominal effort. Kruskal–Wallis test was used to compare the non-normally distributed *CPUE* values of test codends.

$$CPUE = \text{total catch}/\text{nominal effort}$$

$$\text{Nominal effort (for fyke net)} = \text{number of traps} \times \text{fishing days.} \tag{2}$$

Table 1. Mean *CPUE (g/fyke net/day)* values of trial codends by compartments.

Codend	Mean *CPUE* values							*H**	
	Com34	*SG20*	*SG25*	*SG30*	*SRN34*	*SRN42*	*SRN54*		
Codend	10.8	10.3	6.6	6.7	10.8	9.9	6.0	7.0	p<0.05
Cover	5.9	14.7	15.2	14.6	12.6	23.5	15.8	7.8	p<0.05
Total	16.7	25.0	21.8	21.4	23.4	33.4	21.8	2.8	p<0.05

* Kruskal–Wallis *H* value.

3 Results

3.1 Catch composition

The total catch of all specimens from the test codends was 77.3 kg, with 27.8 kg (23.9%) and 49.6 kg (76.1%) in the codends and covers, respectively. The breakdown of the total catch for each codend tested was as follows: 8.1 kg in *Com34*, 12.0 kg in *SG20*, 10.3 kg in *SG25*, 9.4 kg in *SG30*, 11.7 kg in *SRN34*, 15.5 kg in *SRN42* and 10.3 kg in *SRN54*. The breakdown for the covers was as follows: 2.9 kg in *Com34*, 7.3 kg in *SG20*, 7.5 kg in *SG25*, 6.7 kg in *SG30*, 6.8 kg in *SRN34*, 10.8 kg in *SRN42* and 7.6 kg in *SRN54*. *CPUE* (g/fyke net/day) values of codends are listed in Table 1. No significant differences were found between the *CPUE* values of the codends ($p > 0.05$).

The total number of crayfish in the codends (retained) and covers (escapees) and their seasonal distributions are shown in Table 2. A total of 2791 individuals were caught, with sizes ranging from 21.9 (*Com34* summer sampling in *cover*) to 162.1 mm (*SG20* spring sampling in *codend*) *TL*. In all seasons and all experimental fyke nets, the difference between the average lengths of the prey obtained from the codends and covers was found to be significant ($p < 0.05$, Tab. 2). This may indicate that a minimum size selectivity was achieved in all trial groups. This phenomenon is noted more clearly in the length distributions shown in Figure 3. Based on the whole prey, the average size of the crayfish collected from the codends *Com34*, *SG20*, *SG25*, *SG30*, *SRN34*, *SRN42* and *SRN54* was found to be 101.5, 113.3, 119.1, 126.5, 103.7, 107.4 and 122.2 mm, respectively. There was a significant difference between the mean values ($p < 0.05$). Therefore, the increased bar spacing used in grids and the mesh size openness used in codends increased the average length of the catch.

3.2 Size selectivity results

The Akaike information criterion (*AIC*) values for different models are listed in Table 3. The lowest *AIC* value was obtained from Richard model for *Com34* (358.8), *SG30* (98.3) and *SRN42* (484.4); Dual Logit (*Dlogit*) for *SG20* (333.4), *SRN34* (477.6) and *SRN54* (542.0) and Logit model for *SG25* (179.5).

The mean L_{50} and *SR* values with their confidence intervals (*CIs*) are shown in Table 4. The lowest L_{50} values were obtained for *Com34* (9.4 cm), while the highest value was obtained for *SG30* (12.0 cm; Fig. 3). The other L_{50} values from the highest to lowest were 11.3 cm for *SG20,* 11.6 cm for *SG25*, 10.9 cm for *SRN34*, 11.5 cm for *SRN42*, and 11.6 cm for *SRN54*. On the other hand, the *SRs* were 3.1 cm for *Com34*, 1.4 cm for *SG20*, 1.3 cm for *SG25,* 0.6 cm for *SG30,* 2.1 cm for *SRN34,* 2.1 cm for *SRN42* and 1.1 cm for *SRN54*.

The percentages of crayfish below (nP^-) and above (nP^+) the *MLS* and the subsequent and total discard ratio (*Dratio*) for all seasons are given in Table 5. *Com34* had a high retention of small-sized crayfish ($nP^- > 34.6\%$) (Tab. 5), which was consistent with its selectivity curve.

The nP^- values of the sorting grids (9.0% for *SG20*, 0.8% for *SG25* and 0.2% for *SG30*) were lower than those of the mesh codends (19.1% for *SRN34* and 16.9% for *SRN54*), except *SRN42* (6.8%) (Tab. 5). Regarding the *Dratio*, *SG30* had the lowest value (1.01%), while *Com34* and *SRN54* had the highest values of 39.2% and 39.5%, respectively. In addition, the *Dratio*s of the spring and summer seasons were higher than those of the autumn and winter seasons for all codends.

The test codends were directly compared with the delta curves (Fig. 4). All delta plots were significantly different from *Com34* when size selectivity was compared based on *MLS* (10 cm) because the confidence intervals of the delta curves did not contain 0.0.

4 Discussion

Fyke net were tested for the first time with a covered codend design. In this study, the results clearly showed that conventional fyke nets with 34 mm mesh size had low L_{50} values, and these codends did not release sufficient numbers of small-sized crayfish (i.e. below the *MLS* of 10 cm *TL*). In addition, all the test codends investigated showed improved selectivity, and the L_{50} values of *SRN34* (9.4 cm) and *SRN34* (10.9 cm) were close to the 10 cm *MLS* value.

We found that the mean lengths of *P. leptodactylus* increased from spring to winter, and the difference between the seasonal mean lengths was statistically significant ($p < 0.05$). There was an evident increase in average prey sizes from spring to winter (Fig. 3), which could be attributed to their growth. This is relevant to the moulting process, which is important for crustaceans because the increase in size is associated with moulting frequency (Cilbiz, 2021). The process of moulting is inhibited when water temperatures are lower than 10–11 °C (Ackefors et al., 1989; Henttonen et al., 1993; Kouba et al., 2010). Hence, the maximum growth performance occurs during spring and summer, especially in young individuals (Fig. 3). Also, the trappers are more or less efficiently removing larger crayfish from the stock, and thus the size distribution should be skewed towards smaller-sized crayfish in the beginning of the growth season.

Previous selectivity studies conducted in Turkey revealed that when mesh size increases and the mesh configuration changes from diamond to hexagonal geometry with similar

Table 2. Total number of crayfish in codend (retained) and cover (escapees) and their seasonal length distributions.

Codend		Spring		Summer		Autumn		Winter		p^{**}	Total	
		N	*TL Mean ± SE*	*N*	*TL Mean ± SE*	*N*	*TL Mean ± SE*	*N*	*TL Mean ± SE*	*TL*	*N*	*TL Mean ± SE*
Com34	Codend	35	$^{x}91.5 \pm 3.0^{a}$	46	$^{x}96.1 \pm 1.3^{a}$	34	$^{y}111.0 \pm 2.2^{a}$	50	$^{y}106.9 \pm 1.3^{a}$	0.000	165	101.5 ± 1.1^{a}
	Cover	60	$^{x}77.1 \pm 1.7$	64	$^{y}86.6 \pm 1.6$	12	$^{yz}92.7 \pm 5.0$	26	$^{z}98.4 \pm 1.8$	0.000	162	85.4 ± 1.2
	p		0.000		0.000		0.004		0.000			0.000
	Total	95	$^{x}82.4 \pm 1.7$	110	$^{y}90.59 \pm 1.15$	46	$^{z}106.19 \pm 2.38$	76	$^{z}104.0 \pm 1.2$	0.000	327	93.52 ± 0.91
SG20	Codend	23	$^{x}103.0 \pm 4.8^{a}$	11	$^{xy}107.8 \pm 1.3^{bc}$	22	$^{z}120.8 \pm 1.9^{bc}$	43	$^{yz}116.4 \pm 1.4^{b}$	0.000	99	113.3 ± 1.5^{bc}
	Cover	53	$^{x}81.0 \pm 1.7$	81	$^{y}94.2 \pm 0.9$	56	$^{z}105.9 \pm 1.6$	84	$^{z}104.1 \pm 1.0$	0.000	274	97.1 ± 0.8
	p		0.000		0.000		0.000		0.000			0.000
	Total	76	$^{x}87.7 \pm 2.2$	92	$^{y}95.8 \pm 1.0$	78	$^{z}110.1 \pm 1.5$	127	$^{z}108.3 \pm 1.0$	0.000	373	101.4 ± 0.8
SG25	Codend	6	$^{z}128.4 \pm 7.4^{b}$	4	$^{x}105.7 \pm 3.5^{abc}$	23	$^{yz}122.8 \pm 1.7^{c}$	20	$^{xy}114.8 \pm 2.0^{ab}$	0.001	53	119.1 ± 1.6^{cd}
	Cover	29	$^{x}81.8 \pm 1.7$	83	$^{y}96.6 \pm 0.8$	55	$^{z}106.3 \pm 1.4$	95	$^{z}102.9 \pm 0.\ 9$	0.000	262	99.3 ± 0.7
	p		0.001		0.018		0.000		0.000			0.000
	Total	35	$^{x}89.8 \pm 3.5$	87	$^{y}97.0 \pm 0.8$	78	$^{z}111.1 \pm 1.4$	115	$^{z}105.0 \pm 0.9^{d}$	0.000	315	102.6 ± 0.8
SG30	Codend	11	130.8 ± 4.9^{b}	0	–	12	123.5 ± 2.0^{c}	18	125.7 ± 1.5^{c}	0.225	41	$126.\ 5 \pm 1.6^{d}$
	Cover	63	$^{x}82.4 \pm 1.4$	45	$^{y}96.8 \pm 1.1$	54	$^{z}109.0 \pm 1.4$	72	$^{z}106.0 \pm 1.2$	0.000	234	98.6 ± 0.9
	p		0.000		–		0.000		0.000			0.000
	Total	74	$^{x}89.6 \pm 2.4$	45	$^{y}96.8 \pm 1.1$	66	$^{z}111.6 \pm 1.4$	90	$^{z}109.9 \pm 1.3$	0.000	275	102.7 ± 1.0
SRN34	Codend	64	$^{x}92.9 \pm 2.6^{a}$	8	$^{x}97.4 \pm 2.3^{ab}$	29	$^{y}112.8 \pm 1.4^{ab}$	41	$^{y}115.4 \pm 1.8^{b}$	0.000	142	103.7 ± 1.6^{a}
	Cover	129	$^{x}80.5 \pm 0.8$	95	$^{y}89.4 \pm 0.9$	39	$^{z}101.9 \pm 2.1$	56	$^{z}103.5 \pm 1.1$	0.000	319	89.8 ± 0.8
	p		0.000		0.017		0.000		0.000			0.000
	Total	193	$^{x}84.6 \pm 1.1$	103	$^{y}90.0 \pm 0.9$	68	$^{z}106.6 \pm 1.5$	97	$^{z}108.5 \pm 1.2$	0.000	461	94.1 ± 0.8
SRN42	Codend	52	$^{x}97.5 \pm 2.8^{a}$	15	$^{x}105.20 \pm 1.8^{abc}$	23	$^{y}118.5 \pm 1.8^{abc}$	29	$^{y}117.6 \pm 2.0^{b}$	0.000	119	107.4 ± 1.6^{ab}
	Cover	297	$^{x}76.6 \pm 0.7$	90	$^{y}88.9 \pm 1.1$	59	$^{z}106.1 \pm 1.3$	96	$^{z}102.9 \pm 1.0$	0.000	542	86.5 ± 0.7
	p		0.000		0.000		0.000		0.000			0.000
	Total	349	$^{x}79.75 \pm 0.81$	105	$^{y}91.26 \pm 1.09$	82	$^{z}109.60 \pm 1.21$	125	$^{z}106.3 \pm 1.1$	0.000	661	90.3 ± 0.7
SRN50	Codend	8	$^{y}130.7 \pm 6.2^{b}$	7	$^{x}111.3 \pm 1.1^{c}$	18	$^{xy}123.1 \pm 1.9^{c}$	16	$^{xy}121.7 \pm 2.5^{bc}$	0.000	49	122.2 ± 1.6^{d}
	Cover	166	$^{x}79.0 \pm 0.9$	55	$^{y}94.6 \pm 1.5$	52	$^{z}106.8 \pm 1.4$	57	$^{z}105.0 \pm 1.1$	0.000	330	90.5 ± 1.0
	p		0.000		0.000		0.000		0.000			0.000
	Total	174	$^{x}81.4 \pm 1.2$	62	$^{y}96.5 \pm 1.5$	70	$^{z}111.0 \pm 1.4$	73	$^{z}108.7 \pm 1.3$	0.000	379	94.6 ± 1.0
p^{*}			0.000		0.000		0.000		0.000			0.000

p: probability value of *t-test* for *TL* comparing of cover & codend for same experimental gear. p^{*}: probability value of *ANOVA* for *TL* comparing of experimental codends, differences of groups marked with *a, b, c* letters (in column). p^{**}: probability value of *ANOVA* for *TL* comparing of the season for same codend & cover, differences of groups marked with *x, y, z* letters (in rows). *TL*: total length (mm).

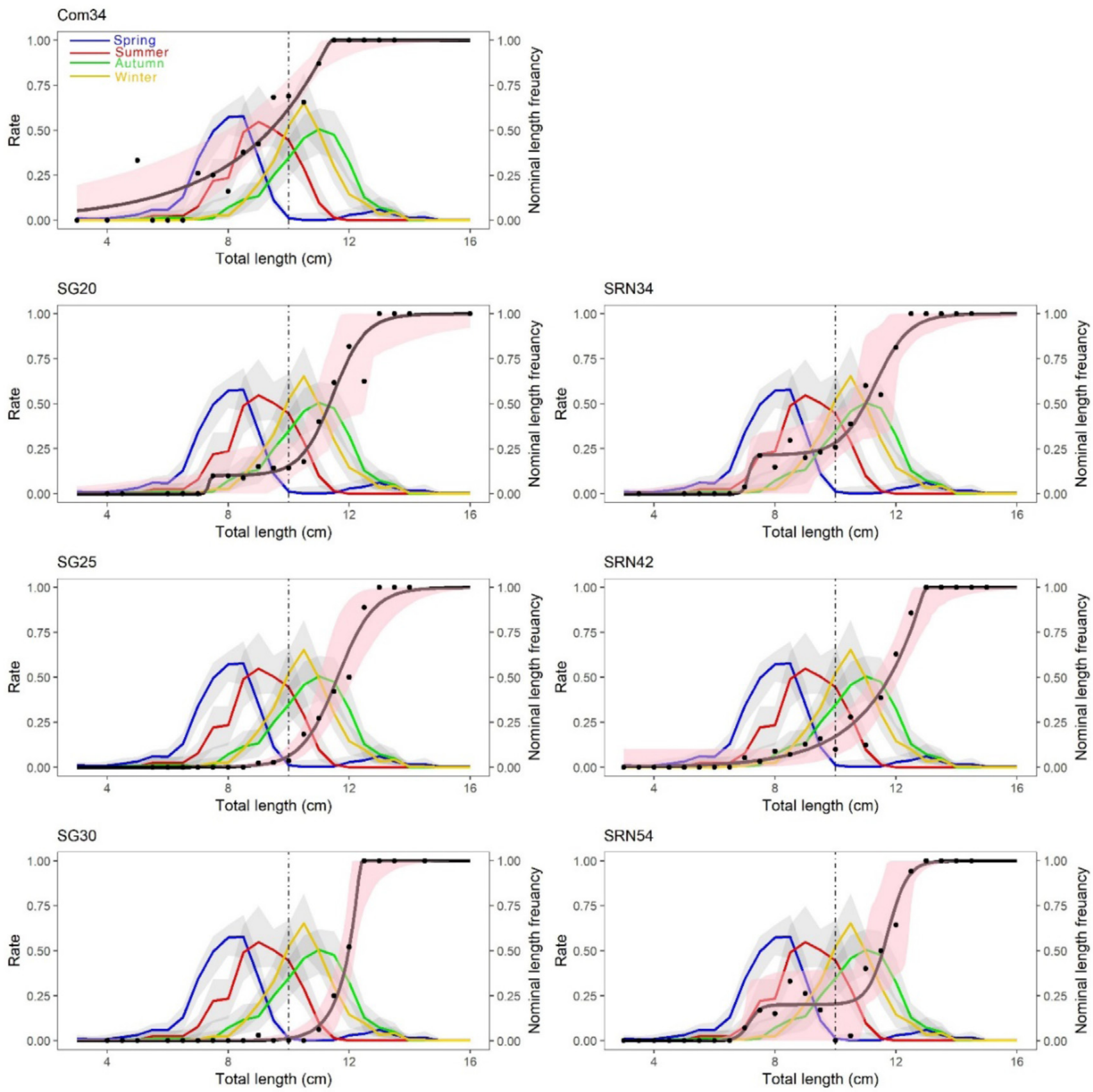

Fig. 3. Selectivity curves with Efron's (1982) confidence intervals (black lines represent the selection curve, vertical dashed lines represent the *MLS* for *P. leptodactylus* and light pink areas describe the 95% *CIs*) and the size distribution of the population of *P. leptodactylus* for the different fishing seasons (light grey areas describe the 95% *CIs*).

Table 3. Summary of the *AIC* values derived from the selectivity models.

Codends	*Logit*	*Probit*	*Gompertz*	*Richard*	*Dual Logit*
Com34	360.4	360.8	368.5	**358.8**	363.1
SG20	338.5	341.3	349.2	334.8	**333.4**
SG25	**179.5**	179.6	184.1	181.4	185.0
SG30	101.4	107.5	121.0	**98.3**	101.1
SRN34	487.0	487.3	491.0	480.4	**477.6**
SRN42	490.3	491.4	496.9	**484.4**	484.8
SRN54	594.3	595.3	602.5	573.3	**542.0**

effective opening sizes, the L_{50} values improve. In a study by Bolat et al. (2010), L_{50} values for 34- and 42-mm diamond mesh codends were determined to be 7.09 cm and 9.93 cm, respectively (Bolat et al., 2010). In another study, while 38-mm diamond mesh yielded a L_{50} value of 8.70 cm, hexagonal mesh of the same size yielded an L_{50} value of 10.23 cm (Bolat and Uçgun, 2019). However, these selectivity studies used the twin trawl method, whereas we analysed the selectivity parameters using the *SELECT* method. Owing to the differences in experimental methods, our results are not comparable to those of Bolat and Uçgun (2019). This is because the *SELECT* method assumes that the catch entering each codend is initially

Table 4. Selectivity parameters and fit statistics for *P. leptodactylus* in the experiments (analysed based on the selected model. *SR*: selection range; *df*: degrees of freedom. The values in parentheses are the Efron's (1982) 95% *CIs*.

Codends	L_{50} (cm)	*SR* (cm)	*p*-value	Deviance	*df*
Com34	9.4 (8.0–9.7)	3.1 (2.0–5.7)	0.65	15.2	18
SG20	11.3 (10.7–12.5)	1.4 (0.2–3.8)	0.96	7.1	15
SG25	11.6 (11.0–12.1)	1.3 (0.7–1.8)	0.99	5.3	16
SG30	12.0 (11.7–12.2)	0.6 (0.2–1.0)	0.99	6.7	17
SRN34	10.9 (9.9–12.0)	2.1 (0.3–4.6)	0.17	22.5	17
SRN42	11.5 (10.5–11.9)	2.1 (1.3–3.9)	0.45	21.4	22
SRN54	11.6 (10.7–12.4)	1.1 (0.3–5.1)	<0.05	41.9	19

Table 5. Fishing efficiency indicators. Fishing percentage of retained specimens below (nP^-) and above (nP^+) the specific *MLS* (10 cm) and the subsequent *Dratio*s (values in parentheses indicate the Efron's (1982) 95% *CIs*.

Codend	Parameters	Seasons				Total
		Spring	Summer	Autumn	Winter	
	Dratio(%)	79.7 (63.2–88.6)	58.7 (46.2–70.3)	11.5 (8.7–17.0)	14.4 (10.9–20.1)	39.2 (27.6–52.9)
Com34	nP^- (%)	30.6 (21.8–50.4)	39.0 (33.0–57.7)	41.5 (31.8–59.0)	45.1 (39.1–63.0)	34.6 (26.8–54.6)
	nP^+ (%)	97.5 (91.5–99.1)	69.9 (65.8–83.5)	86.9 (82.6–92.6)	81.5 (77.5–89.5)	82.8 (79.0–90.3)
	Dratio(%)	53.5 (2.0–75.9)	55.0 (9.1–72.4)	5.7 (0.6–12.5)	8.4 (0.9–17.4)	24.9 (1.7–44.7)
SG20	nP^- (%)	7.9 (0.2–17.5)	10.2 (0.7–22.2)	10.4 (1.0–22.6)	11.3 (1.1–24.7)	9.0 (0.5–20.3)
	nP^+ (%)	86.0 (65.8–95.8)	21.2 (14.4–32.8)	46.1 (33.5–63.9)	37.4 (28.6–52.9)	41.6 (32.3–56.5)
	Dratio(%)	6.7 (0.8–20.6)	19.9 (5.0–34.6)	1.1 (0.2–2.8)	1.9 (0.3–4.4)	3.7 (0.6–9.9)
SG25	nP^- (%)	0.5 (0.0–1.5)	1.2 (0.2–3.0)	1.5 (0.3–3.6)	1.8 (0.4–4.3)	0.8 (0.2–2.3
	nP^+ (%)	80.9 (59.4–92.0)	11.8 (5.9–22.1)	36.6 (24.9–54.7)	28.0 (19.0–42.7)	32.5 (22.7–48.1)
	Dratio(%)	1.2 (0.00–15.4)	14.5 (0.00–54.1)	0.3 (0.00–1.8)	0.6 (0.00–3.1)	1.0 (0.00–7.9)
SG30	nP^- (%)	0.1 (0.00–1.2)	0.2 (0.00–1.6)	0.3 (0.00–1.7)	0.3 (0.0–2.0)	0.2 (0.0–1.4)
	nP^+ (%)	84.4 (59.3–90.6)	3.2 (0.2–8.7)	24.6 (16.0–35.0)	17.1 (10.4–25.1)	22.7 (14.8–32.3)
	Dratio(%)	70.8 (10.3–84.0)	59.6 (22.7–74.1)	9.2 (2.4–16.8)	12.5 (3.9–20.8)	35.8 (7.3–51.9)
SRN34	nP^- (%)	17.2 (1.0–27.5)	21.3 (4.6–34.2)	21.3 (5.3–34.8)	23.1 (7.2–37.4)	19.1 (2.7–30.7)
	nP^+ (%)	89.0 (75.1–95.8)	34.5 (26.1–47.8)	57.4 (45.2–72.5)	49.2 (38.8–63.6)	52.6 (42.3–66.4)
	Dratio(%)	53.9 (10.4–76.3)	52.0 (21.1–64.6)	7.0 (1.9–11.4)	8.6 (2.8–12.6)	22.0 (5.7–37.1)
SRN42	nP^- (%)	7.9 (0.8–16.0)	11.3 (2.3–22.0)	12.3 (2.6–23.6)	10.3 (2.6–16.8)	6.8 (1.4–11.8)
	nP^+ (%)	84.9 (63.6–90.5)	26.4 (15.1–46.9)	44.6 (36.8–63.5)	33.4 (22.7–44.3)	37.4 (26.7–48.4)
	Dratio(%)	68.8 (0.0–84.6)	68.0 (0.0–76.8)	10.4 (0.0–17.3)	14.5 (0.0–22.3)	39.5 (0.0–56.0)
SRN54	nP^- (%)	15.5 (0.0–29.9)	18.6 (0.00–36.4)	18.4 (0.00–34.5)	19.7 (0.0–38.2)	16.9 (0.0–33.0)
	nP^+ (%)	87.9 (67.8–95.6)	22.2 (2.9–39.5)	43.0 (28.3–61.1)	35.2 (21.1–51.1)	39.9 (24.5–55.5)

equal. This assumption is convenient for active types of fishing gear, such as trawl nets, but it is difficult to employ for passive fishing methods, such as fyke nets, because crayfish can instinctively avoid or be attracted to fishing gears, which can affect selectivity. For example, when young individuals encounter predators such as large male crayfish or freshwater crabs in the codends, they might not prefer to enter the nets. During the reproductive period, the presence of a female crayfish in the nets may also attract male crayfish to enter the nets. Moreover, the fyke nets were connected to each other and spread over a wide area. Thus, the environmental characteristics of the fishing ground may not be homogenous. Because juveniles can hide in seagrass and meadows, smaller individuals are more likely to be caught in these areas.

These issues contribute to the lack of an accepted approach for fyke net selectivity studies employing the *SELECT* method. The use of covered codends is the simplest and most effective technique to determine selectivity. Selectivity parameters can be calculated from a single haul. Each haul is an experiment in itself; the repetition of hauls in this method is done to improve the data and reduce sampling errors. It is also relatively easy to implement (Jones, 1984; Millar and Walsh, 1992; Parrish and Pope, 1963; Pope et al., 1975; Wileman et al., 1996). Recently, the covered codend technique has been preferred for many selectivity studies based on the logistic model (Noack et al., 2017; Tokai et al., 2019).

Sorting grids were originally developed for species separation in shrimp trawl fisheries (Isaksen et al., 1992). Given their success at species separation, grids have become mandatory in several fisheries, especially for trawling (Broadhurst and Kennelly, 1996; ICES, 1998; He and Balzano, 2007; Sistiga et al., 2008). In this study, the grids were easily installed in the fyke nets. Due to the fact that stiff rigged nets and sorting grids were directly attached to the end circle (the harvesting point of the fyke net), caught individuals could not

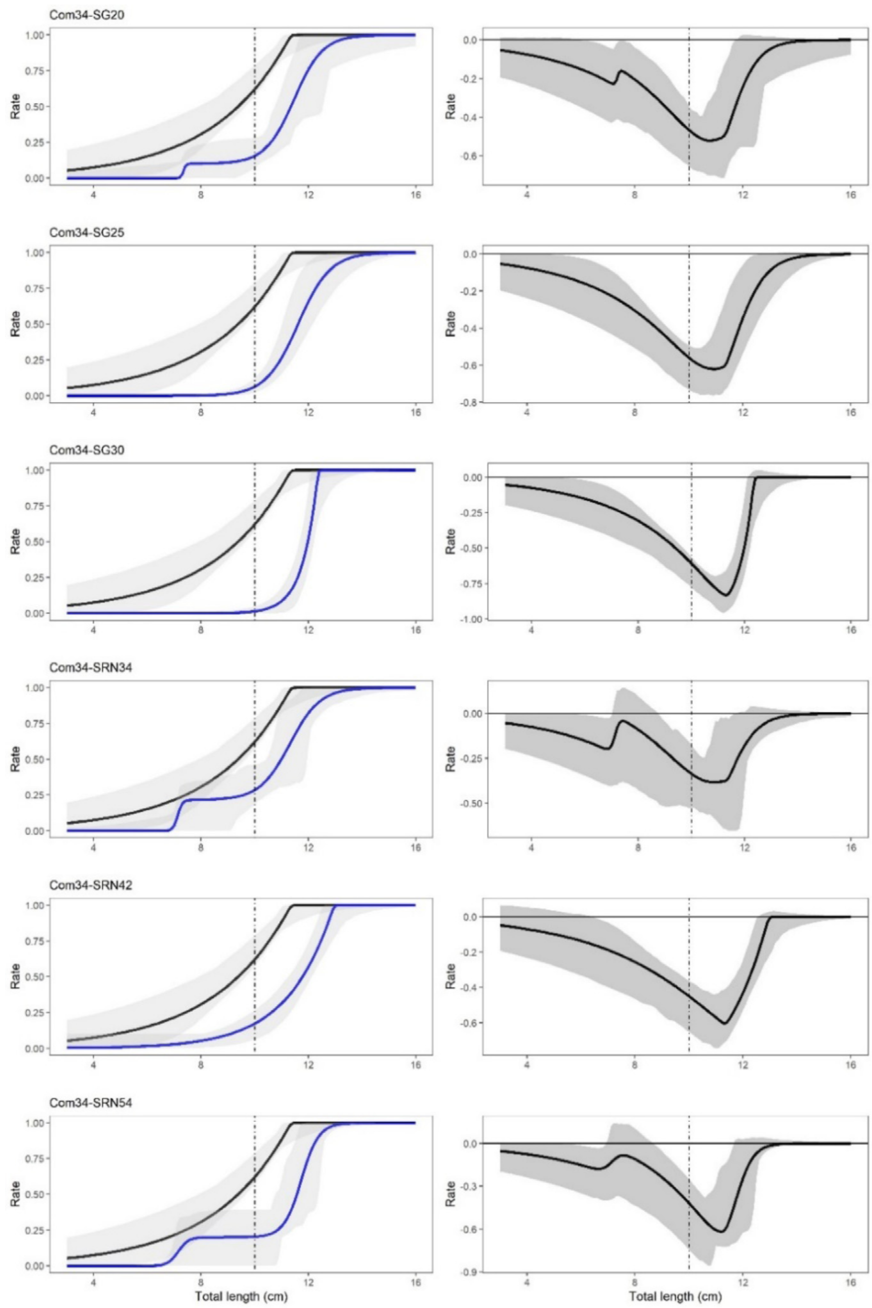

Fig. 4. Left: comparison of the selection curves of commercial fyke nets with experimental codends (black lines represent *Com34*, blue lines represent the experimental codends, vertical dashed lines represent the *MLS* for *P. leptodactylus* and light grey areas describe 95% *CIs*). Right: delta curves for each pair of codends (black curves indicate the fitted delta curves and dark grey areas describe the 95% *CIs*).

be directly harvested from the codend. Further experiments are needed to develop a system that can be easily opened to facilitate harvesting. In this study, nP^{-} ratios of sorting grids were more acceptable than stiff rigged nets. This might be due to the body structure of crayfish, with their many limbs and thorny structures. These can significantly reduce the number of escapees when in contact with the nets.

Sorting grids were originally developed for species separation in shrimp trawl fisheries. (Isaksen et al., 1992). Because many designs have been investigated, grids have become mandatory in several fisheries, especially for trawling (Broadhurst and Kennelly, 1996; ICES, 1998; He and Balzano, 2007; Sistiga et al., 2008). In this study, the grids were easily installed in the fyke nets. Due to the fact that stiff rigged net and sorting grids were directly attached to the end circle (at the same time it is harvesting point of the fyke net), caught individuals could not be harvested from codend due to applied modification. Further experiments for conventional usage, studies concentrate on the system that can be easily opened and the product can be easily harvested. In this study, nP^{-} ratio of sorting grids were more acceptable than stiff rigged nets. This might be due to the body structure of crayfish, with their many limbs and thorny structures. These can significantly reduce the number of escapees when in contact with the nets.

The presence of too many limbs and thorny structures in the crayfish body can significantly reduce their escape from the nets. It can be explained based on the fact that small-sized individuals (in terms of *TL*) who had the potential to escape from the nets were caught in the codends. On the other hand, the *SRs* of the sorting grids were narrower than those of the net groups, except for *SRN54*, which easy passage through the smooth grid bars.

Initially, the optimal bar spacing for *MLS* was predicted as 25 mm, but the study results show that 25 mm bar spacing resulted in higher L_{50} values than *MLS.* We presumed that crayfish pass through the grid bars bilaterally in a caudo-cranial direction (tail to head). However, it was observed that crayfish escape mainly in the dorsoventral direction. Because their dorsoventral length was shorter than the length between the lateral axes, their passage rates through the 25 mm grids were much higher than expected.

5 Conclusion

In conventional fyke nets, the L50 values are too low when considering the *MLS* (10 cm *TLs*). We have shown that the selectivity can be easily improved using an *SRN* and *SG*. Achieving this benefit requires no major changes to the fyke net's solid structures (rings), only to the codend netting, which is easily modified. The commercial codend has a 39.2% of discard ratio, but grid usage can potentially reduce the discard ratio to 1.0%. Of course, this situation brings economic losses with it. For the grids to be accepted by the fishermen, their economic losses must be at a minimum. With regard to the *MLS*, optimum results were obtained from *SG20* (in terms of minimum economical loss and discard ratio). Reducing the discard rates in commercial fishing will contribute significantly to the sustainability of natural stocks in the long run. According to the current *MLS* application, fishermen are required to select crayfish under 10 cm *TL* from the harvested product on the boat and return them to the lake (lived, injured or died). This requires extra labour and time, negatively affecting the economic profitability of fishing. However, fishermen will likely pay greater attention to the grid system, which successfully improved crayfish selectivity and will not impose extra workload on them. However, for conventional usage, some modifications need to be investigated to easily open and close the grids and stiff riggings at the end of the nets for dumping the catch onboard.

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Appendix: A

A.1 Size selectivity analysis

In this study, we were interested in the average size selection in hauls, as this would provide information about the average consequences of the size selection process when codends were applied in fisheries. Different parametric models $r_{codend}\,(l,\boldsymbol{v_{codend}})$ were tested for the codend size selection. $\boldsymbol{v_{codend}}$ is a vector with the parameters of the model. The purpose of the analysis was to estimate the values of the parameter $\boldsymbol{v_{codend}}$ that make experimental data (average hauls) most likely be observed. Thus, the following formula was derived, which corresponds to the maximum likelihood for the observed experimental data:

$$-\sum_{j=1}^{m}\sum_{l}\{nC_{lj}\times ln(r_{codend}(l,\mathbf{v_{codend}}))+nCC_{lj}\times ln(1.0-r_{codend}(l,\mathbf{v_{codend}}))\}. \quad (A.1)$$

The outer summation in expression (3) comprises the hauls conducted with a specific codend and the inner summation over length classes l in the data. Four different models were chosen as basic candidates to describe $r_{codend}\,(l,\ \boldsymbol{v_{codend}})$ for each codend and species: Logit, Probit, Gompertz and Richard. The first three models were fully described by the two selection parameters L_{50} and *SR* (difference in length between crayfish with 75% and 25% probability of being retained), while the Richard model required one additional parameter ($1/\delta$) that describes the asymmetry of the curve. The formulas and additional information for the four selection models can be found in Lomeli (2019). However, because several codend designs (Fig. 2) included more than one selection device (both meshes and grids), a dual selection model *Dlogit* was also considered as a candidate for $r\,(l,\ \boldsymbol{v_{codend}})$:

See equation (A.2) below.

$$r_{codend}(l,\boldsymbol{v_{codend}})=\begin{cases} Logit(l,L_{50},SR)=\dfrac{exp\left(\frac{\ln(9)}{SR}\times(l-L_{50})\right)}{1.0+exp\left(\frac{\ln(9)}{SR}\times(l-L_{50})\right)}\\ Probit(l,L_{50},SR)\approx\Phi\left(\left(\frac{1.349}{SR}\times(l-L_{50})\right)\right)\\ Gompertz(l,L_{50},SR)\approx\exp\left(-exp\left(-\left(0.365+\frac{1.573}{SR}\times(l-L_{50})\right)\right)\right)\\ Richards\left(l,L_{50},SR,\frac{1}{\delta}\right)=\left(\dfrac{exp\left(logit(0.5^{\delta})+\left(\frac{logit(0.75^{\delta})-logit(0.25^{\delta})}{SR}\right)\times(l-L_{50})\right)}{1+exp\left(logit(0.5^{\delta})+\left(\frac{logit(0.75^{\delta})-logit(0.25^{\delta})}{SR}\right)\times(l-L_{50})\right)}\right)\\ Dlogit\,(l,C_1,L_{50_1},SR_1,L_{50_2},SR_2)=\left(1.0-C_1\times\left(1.0-Logit\,(l,L_{50_1},SR_1)\right)\right)\\ \qquad\times Logit\,(l,L_{50_2},SR_2)\end{cases} \quad (A.2)$$

where Φ is the cumulative density function for a normal distribution.

Evaluating the ability of a model to describe data sufficiently is based on calculating the corresponding p-value, which expresses the likelihood to obtain at least as big as the discrepancy between a fitted model and observed experimental data by coincidence. Therefore, for a fitted model to be a candidate model for size-selection data, the p-value should not be below 0.05 (Wileman et al., 1996). In case of a poor fit statistic ($p < 0.05$), the residuals were inspected to determine whether the poor result was due to structural problems when modelling the experimental data using the different selection curves or to the overdispersion of the data (Wileman et al., 1996). The selection of the best model among the five considered in equation (A.2) was based on Akaike Information Criterion (*AIC*) values. The selected model was the one with the lowest *AIC* value (Akaike, 1974).

Once the specific size selection model was identified for a particular codend, bootstrapping was applied to estimate the confidence limits for average size selection. The software tool *SELNET* (Herrmann et al., 2012) was used for size selection analysis, and a double-bootstrap method was implemented in this tool to obtain the confidence limits for the size selection curve and corresponding parameters. This bootstrapping approach was identical to the one described in Millar (1993) and considered both within-haul and between-haul variations. The hauls for each codend were used to define a group of hauls. To account for between-haul variations, an outer bootstrap resample with replacement from a group of hauls was included in the procedure. Within each resampled haul, the data for each length class were bootstrapped in an inner bootstrap with replacement to account for within-haul variations. Each bootstrap resulted in a 'pooled' set of data, which was analysed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. For each analysed species, 1000 bootstrap repetitions were conducted to estimate the Efron's (1982) 95% confidence intervals (CIs) (Herrmann et al., 2012).

A.2 Inferring the differences in size selectivity between codends

Efron's (1982) 95% *CIs* for $\Delta r(l)$ were obtained based on the two bootstrap populations of the results (1000 bootstrap repetitions in each). Because bootstrap resampling was random and independent of the two groups of results, it was deemed valid to generate a bootstrap population for the difference based on equation (A.1), which generated two bootstrap files (Herrmann et al., 2018):

$$\Delta r(l)_i = r_{test}(l)_i - r_{baseline}(l)_i i \in [1 \ldots 1000], \tag{A.3}$$

where i is the bootstrap repetition index. Significant differences in size selection between codends were obtained if the 95% *CIs* for the delta curves had length classes that did not overlap.

A.3 Estimation of fishing efficiency indicators

To estimate these performance indicators, the size selection curves predicted for each codend were first applied to the population of narrow-clawed crayfish entering the fishing gears. This was estimated from the population entering the gears during the experimental fishing. Because the population size structure ($nPop_l$) of narrow-clawed crayfish varies between seasons, the evaluation was performed separately for each season. This was obtained based on the data from all hauls for all codend designs during a specific season by summing the catches in codends and covers. Uncertainties in populations were obtained by double bootstrapping, following the approach described by Melli et al. (2020). Then, the percentage of individuals below (nP^-) and above (nP^+) the *MLS* (10 cm) for each codend in each season was calculated. Ideally, nP^- and *nDiscard* should be low (close to 0), while nP^+ should be high (close to 100). The indicators were estimated in the different codends by:

$$nP^- = 100 \times \frac{\sum_{l<MS}\{r_{codend}(l, \mathbf{v_{codend}}) \times nPop_l\}}{\sum_{l<MS}\{nPop_l\}},$$

$$nP^+ = 100 \times \frac{\sum_{l>MS}\{r_{codend}(l, \mathbf{v_{codend}}) \times nPop_l\}}{\sum_{l>MS}\{nPop_l\}},$$

$$nDiscard = 100 \times \frac{\sum_{l<MS}\{r_{codend}(l, \mathbf{v_{codend}}) \times nPop_l\}}{\sum_{l}\{r_{codend}(l, \mathbf{v_{codend}}) \times nPop_l\}}. \tag{A.4}$$

All indicators (nP^-, nP^+ and *nDiscard*) were estimated with uncertainties for each codend and population scenario, using a bootstrap set for $r_{codend}(l, \boldsymbol{v_{codend}})$ and $nPop_l$. Based on Herrmann et al. (2018), the bootstrap set to calculate for indicator values was obtained based on each bootstrap repetition result, applying $r_{codend}(l, \boldsymbol{v_{codend}})$ and $nPop_l$ simultaneously in equation (A.4). Finally, based on the resulting bootstrap set, 95% *CIs* were obtained for each of the indicators. All the analyses about the indicators were conducted using the software *SELNET* (Herrmann et al., 2012).

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