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Impact and size selectivity of fishing gears used in estuarine crab fisheries

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ABSTRACT

Crustacean fisheries have expanded in the last decade due to the high economic value of the species. However, estuarine crustacean fisheries remain poorly studied compared with marine crustacean fisheries. In Portugal, the European green crab (*Carcinus maenas)* may become increasingly important for the fishing industry and seafood production in general, especially in the current context of overexploitation of estuarine traditional fisheries resources. The unknown ecological impact of crab fishing gear and its size-selectivity characteristics constrain gear regulations by fisheries authorities. We developed an integrated study over three years to analyse a *C. maenas* fishery in three Portuguese estuarine systems aiming to: 1) describe the fishing characteristics and *modus operandi* of the fishing gears; 2) analyse gear selectivity and catch rates; 3) analyse environmental impact of fishing gears; 4) Contribute to supporting better regulations for the fishery. Two types of crab fishing gear are used, box traps and drop nets. Daily catches of green crabs varied by gear, system, and month, with the highest catches observed in box traps during the warmest months. Selectivity studies indicate that a mesh size of 18 mm in box traps and 30 mm in drop nets would allow crabs larger than the minimum landing size (40 mm carapace width) to be targeted while maximising catch rates. However, regardless of the mesh size, the catch from both gears will need to be sorted to exclude juveniles from the catch. The bar spacing, which allows crabs to be sorted according to the minimum landing size, is 17 mm. Gears present none (drop nets) or low by-catch (220 g or 23 individuals/40 box traps), which was promptly discarded, indicating a low impact on estuarine communities. The methodology used in this study, which combines ecological impacts and technical gear issues (selectivity), can be directly applied to enforce regulations and improve sustainable exploitation of socio-economically important artisanal fisheries.

1. Introduction

Crustacean fisheries have grown fast worldwide, mainly due to their high economic value (Smith and Addison, 2003). Annually, between 2016 and 2023, approximately 14.5 million tons of crustacean species were harvested, representing 8 % of the world's total marine biological resources supply (FAO, 2016; Boenish et al., 2022; Sun et al., 2023). Approximately 50 % of this catch is derived from the harvesting of wild stocks, a sector that has expanded in last decades due to global economic development and population growth. However, the depletion of marine biological stocks is a concern worldwide (Penn et al., 2019; Sun et al., 2023). Given the high value of crustaceans, these fisheries are particularly vulnerable to intensive exploitation, such as shrimps, lobsters and crabs (ICES, 2023).

The most commonly harvested crab species include the gazami crab (*Portunus trituberculatus*) and the blue swimm ing crab (*Portunus pelagicus*), which are widely caught in the Indian Ocean; the blue crab (*Callinectes sapidus*) and snow crab (*Chionoecetes opilio*), which are harvested on the eastern coast of the USA; the red king crab (*Paralithodes camtschaticus*) caught on the western coast of the USA; and the edible crab (*Cancer pagurus*), and snow crab (*Chionoecetes opilio*), caught along the European Atlantic coast. These species collectively contribute to more than one million tonnes of catches annually (Penn et al., 2019). In general, the fisheries for coastal or deep marine crab species have been well-studied (Stagg and Whilden, 1997; Johnston et al., 2011; Liu et al., 2013; Seitz et al., 2014), with annual scientific monitoring and stock assessments conducted through both national and international surveys (ICES, 2023).

However, the fishery of estuarine crab species remains poorly studied, such is the case of the European green crab (*Carcinus maenas*) fishery. This crab is one of the most prominent benthic predators in marine and estuarine intertidal areas (Klassen, Locke.. 2007; Waser

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et al., 2018). *Carcinus maenas* is a small decapod, native to the coasts and estuaries of the Northeast Atlantic (Crothers, 1967; Carlton and Cohen, 2003; Rewitz et al., 2004). Over the past century, it has expanded its geographic distribution and settled in five major regions of the world, where it is considered a highly invasive species (Thresher et al., 2000). The extensive spread of *C. maenas* is largely attributable to its rapid growth, reaching the sexual maturity within a year, high fecundity, long spawning season, high phenotypic plasticity and tolerance to variations in salinity and temperature (Amaral et al., 2009; Young and Elliott, 2020; Monteiro et al., 2022, 2023, 2025). Although *C. maenas* has a lower economic value than the previously mentioned marine crab species, it has high socio-economic local importance in estuarine and lagoon regions (Sheehan et al., 2008; Leitão and Monteiro, 2022). *Carcinus maenas* present a huge market in some European and American regions (Gomes, 1991; Young and Elliott, 2020; Monteiro et al., 2024a). In native regions, both *C. maenas* and *Carcinus aestuarii* (a co-generic species of *C. maenas* that inhabits the Mediterranean Sea) are highly abundant species in European estuaries and lagoons (Glamuzina et al., 2017; Monteiro et al., 2023). Consequently, green crabs have been harvested using traps in Europe since the 20th century, representing a fishery with high socio-economic importance in Portugal and the UK (Gomes, 1991; Sheehan et al., 2008; Monteiro et al., 2024a). Crabs are consumed in restaurants, manufactured by shellfish companies into crab sticks, soups, and stock cubes, and used in octopus and recreational fisheries as live bait (Leitão et al., 2021, 2023). In non-native regions, the target fishery for the green crab, *C. maenas,* has increased since the beginning of the 21st century. Green crabs are caught with fukui traps for culinary purposes (Parks and Thái, 2019; Greiner et al., 2021) and to be used as bait in lobster fisheries (St-Hilaire et al., 2016; McKenzie et al., 2022).

Despite the high socio-economic importance of the green crab fishery in Europe (native region), it remains poorly understood. One of the few studies to be conducted in this region was carried out in Ria de Aveiro, a Portuguese coastal lagoon (Gomes, 1991). In contrast, more effort has been directed toward addressing non-native *C. maenas* populations and the operational aspects of these crab fisheries, particularly in the USA and Canada (Bergshoeff et al., 2019; Favaro et al., 2020). The invasive status of *C. maenas* in these regions has prompted the development of various programmes to enhance fishing methods' efficiency, with the aim of mitigating the impact of this species (McKenzie et al., 2022). Initial attempts to manage *C. maenas* through eradication in North American regions were unsuccessful. Consequently, fishing this species has become the predominant strategy to control *C. maenas* invasions in North America (Duncombe and Therriault, 2017; Bergshoeff et al., 2019).

In Portugal, *C. maenas* is caught in estuarine and lagoon systems using traps, nets, and hand collection (Monteiro et al., 2024a). The majority of green crabs are sold to fishers who utilise them as live bait for octopus and recreational fishing (Leitão et al., 2023; Monteiro et al., 2024a). In addition to its use as bait, green crabs are also sold to Spanish shellfish companies in the northern region of Portugal (Monteiro et al., 2024a). At the outset of the exploitation of *C. maenas* fishing in Portugal, the majority of the catches were exported to Spain. However, these companies only desired larger crabs with a carapace width (CW) greater than 50 mm. Consequently, in alignment with Spain's size preferences, a minimum landing size (MLS) of 50 mm of CW was established in Portugal (Portaria nº 27/2001).

Since 2000, the MLS defined at 50 mm CW led to frequent problems for commercial crabbers. Fishing gears and the catches were seized by the authorities due to the use of non-compliant landing regulations and the catching of green crabs bellow the MLS. Nevertheless, crabbers were aware that this MLS was high, particularly given that the majority of ovigerous females caught had a CW between 30 and 40 mm (Monteiro et al., 2024a). This traditional knowledge, defined as local ecological knowledge (LEK) (Cosham et al., 2016; Obregón et al., 2022), was corroborated with scientific studies conducted along the Portuguese coast, which reported that *C. maenas* reach sexual maturity at around 30 mm of CW and peak of spawning season between October and April (Souza et al., 2011; Monteiro et al., 2025). In 2023, based on irrefutable evidence that 50 mm CW represented an exceedingly high value (Leitão and Monteiro, 2022), the MLS was reduced to 40 mm CW (Portaria nº 255/2022), which still allows females to spawn prior to capture (Monteiro et al., 2025). However, this is the unique regulation of crab fishery in Portugal, and the fishing gears employed to catch green crabs are not regulated. Consequently, crabbers employ general drop nets and cuttlefish traps that are not specifically designed to target crabs. Therefore, it is necessary to characterise the fishing gears used in the Portuguese green crab fishery and determine the mesh size required to select crabs on, or above the MLS, which allows them to spawn at least once prior to capture. The main objectives of this study were to: 1) describe the fishing characteristics and *modus operandi* of the fishing gears used in Portugal; 2) analyse gear selectivity and catch rates of the fishing gears; 3) analyse the environmental impact of crab fishing gears on the estuarine community; 4) Contribute to supporting better regulations for the green crab fishery.

2. Materials and methods

2.1. Study area and fishing licenses

This study was requested by fishers to regulate the crab fishery with box traps targeting crabs, a smaller mesh than that currently allowed (cuttlefish trap). At the outset of this study, meetings were held with representatives of fishing associations. Information about communities engaged in the green crab fishery was obtained during these meetings. With this initial information, we contacted commercial crabbers from each system and assessed their availability to collaborate in the study. Crab fishing licences were provided by the Directorate-General for Natural Resources, Safety and Maritime Services (DGRM) for crabbers who agreed to collaborate with the study. License holders were obligated to: 1) provided standardized data throughout logbooks, e.g. landings and effort information (number of fishing gears); 2) record fishing trips (GPS data); 3) explain how to operate fishing gears; 4) conduct monthly scientific surveys for collect demographic data (size-length frequency data collected onboard commercial boats by the scientific team); 5) perform scientific experiments with the scientific team, such as selectivity mesh size experiments. Licences were provided to crabbers from the northern (Ria de Aveiro), central (Sado River), and southern (Ria Formosa) regions of Portugal (Fig. 1). For this study, gear dimensions and mesh sizes (excluding selectivity studies) within gear types were kept similar regardless of the system (Table 1). The Ria de Aveiro crabbers utilised drop nets, the Sado River crabbers employed box traps, and the Ria Formosa crabbers employed both fishing gears.

2.2. Experimental design

In each system, field sampling was conducted monthly between January 2019 and April 2022 on board commercial artisanal boats operated by professional crabbers. Fishing trips were conducted with both baited drop nets and box traps, set at an average depth of 2–3 m and at a minimum distance empirically defined by crabbers to maximise catch rates, i.e. to avoid gear saturation and maximise bait attraction. In the field samplings the type of gear used (box trap or drop net), the number of gears used, the bait used, the total catch per gear, and the soak time of the gears were recorded. Furthermore, the technological characteristics of the fishing gear employed in the field samplings were quantified, including the main characteristics and specifications, such as materials and dimensions, including mesh size, length, and bait opening. Additionally, the *modus operandi* of the gear was recorded. In each scientific field sampling the water temperature was measured using a handheld meter (VWR Symphony SP90M5), the total catch was weighed, and for size-length frequency data a sub-sample of

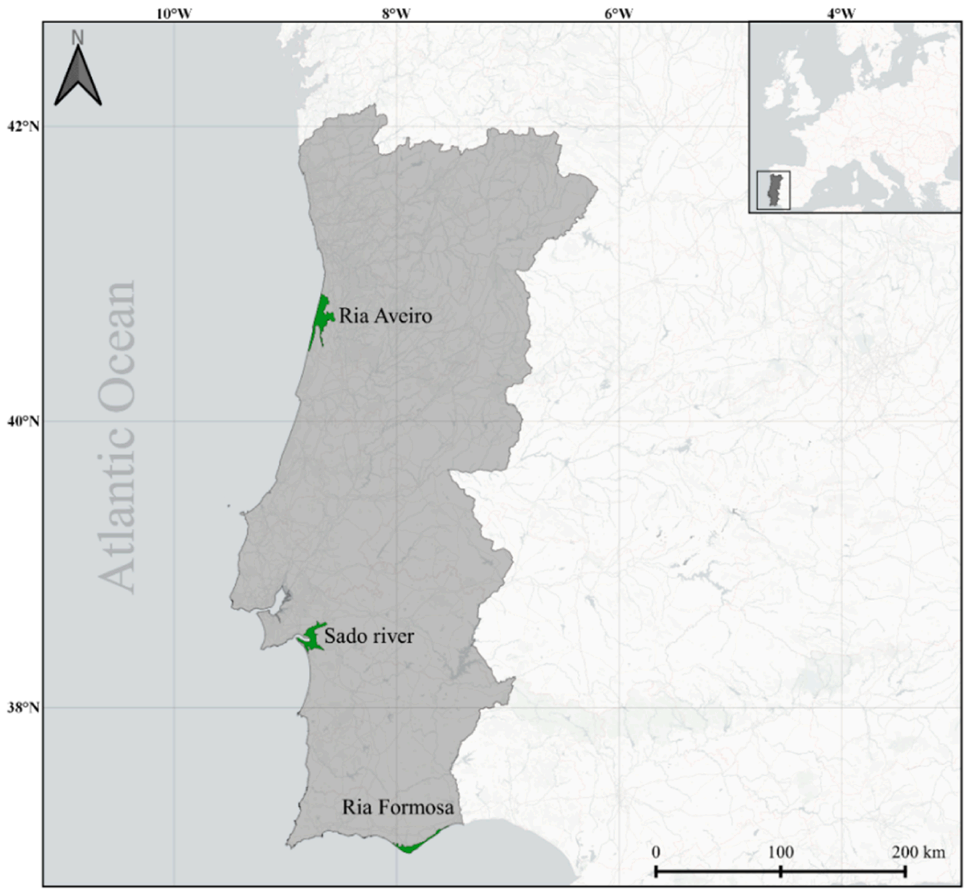

Fig. 1. Geographical location of the different systems; at grey coloration Portugal and with green coloration the areas of study: Ria Formosa, Sado river and Ria de Aveiro.

Table 1
Main characteristics and technical specifications (dimensions and materials) of the fishing gears used in the fishery for European green crab in the Portuguese coast.

	Box traps	Drop nets
Frame		
Gear shape	Rectangular	Circular
Length (cm)	45	-
Width (cm)	34	-
Height (cm)	16	-
Diameter (cm)	-	50
Material	Iron	Iron
Rope		
Length (meters)	3	3
Material	Polyethylene (twisted PE)	Polyethylene (twisted PE)
Net		
N° of entrances	2	1
Mesh size (cm)	1.8	3
Mesh shape	Square	Diagonal
Material	Rigid Polyethylene	Net Nylon, Polyester
Systems where the gear is used	Lima river Sado river Ria Alvor Ria Formosa	Ria Aveiro Ria Alvor Ria Formosa

approximately three kg of green crabs was randomly collected from the total catch for further laboratory measurements. In the laboratory, the carapace width of all crabs in the subsample was measured to characterise the size distribution (carapace width - CW) of the crab population. To assess the impact of both gears at ecological level, all macrofauna and fish specimens of by-catch were collected in field samples at Ria Formosa. In laboratory, all the specimens were measured (size and weight) and identified to the lowest possible taxonomic level.

Selectivity experiments were conducted in Ria Formosa for both fishing gears with the objective of determining the optimal mesh size for the exploitation of green crabs. In order to observe the effect of the gear and mesh size rather than the bait itself, all the gears were baited with the same bait, chub mackerel. Three different mesh sizes, which corresponded to the dimensions of commercially available in the fishery market, were tested for both fishing gears. Drop nets were tested with mesh sizes of 30, 40, and 50 mm of stretched mesh. For the box traps, square hard mesh sizes of 8, 18, and 30 mm of width were tested. In each gear, a cover bag with a 2 mm mesh was sewn over the gear (cover method). This method ensured that any crabs that passed through the mesh or trap were retained in the cover bag. At the end of the experiment, the specimens that were retained in the gear and the cover bag were measured. For size-selective experiments within each gear mesh size, a total of 15 individual hauls were conducted.

2.3. Data analysis

2.3.1. Fishing catches

To characterise the operations and catches of green crab fishing, different catch indicators were determined:

1) **CPUE per gear:** The catch per unit of effort for each gear type (CPUE-gear) was standardised based on the average soak time, which was calculated as 24 hours for box traps and 30 minutes for drop nets. Each individual gear soaking in the fishing ground was considered an independent sample. The average CPUE-gear between systems that employ the same fishing gear (Box traps: Sado river and Ria Formosa;

Drop nets: Ria Aveiro and Ria Formosa) was compared using a parametric T-test for independent samples.

2) **CPUE per day:** The catch per unit of effort in a fishing day (CPUE-day) was calculated based on the cumulative sum of total catches, for each fishing gear and system per crabber. The CPUE-day was estimated by considering the total daily catches and the total fishing gears used and was standardised based on the average number of gears used, namely 40 box traps and 150 drop nets per crabber, regardless of the systems. Differences in CPUE-day were tested between systems and also regardless of the system using a parametric T-test for independent samples. The aim was to observe whether the CPUE-day varied according to the system and also to the gear type. Furthermore, the intra- and interannual changes in CPUE-day of Ria Aveiro (drop nets) and Sado river (box traps), were analysed by two-way analyses of variance (ANOVA), with CPUE-day as the response variable and years and months as the explanatory variables. The relationship between the monthly mean daily green crab catches and the mean monthly water temperature was explored through cross-correlations (Pearson correlation test).
3) **Gear soaking time:** The average soak time for each fishing gear in each system was recorded based on field data. To analyse possible differences in the average soaking time between the systems (as fishing effort time units), a T-test for independent samples was conducted.

2.3.2. Green crab catches size composition and by-catch species

Green crabs analysed in the laboratory were grouped into 2 mm carapace width (CW) size classes to analyse the catch size-frequency distribution for both gears and to determine the proportion of individuals caught below and above the minimum landing size (MLS) stipulated for *C. maenas* (40 mm of CW) and the biological size at maturation (SM) in the Portuguese systems (30 mm of CW). Differences in the frequency distribution of CW class-size between gears were assessed using the two-sample Kolmogorov-Smirnov test (two-samples KS test). In addition, in Ria Formosa, relationships between monthly mean daily catches, by-catch in weight (kg), and water temperature were examined using cross-correlations (Pearson correlation). The statistical analysis of Sections 2.3.1 and 2.3.2 was carried out using IBM SPSS Statistical 29 software (significance error level $\alpha = 0.05$).

2.3.3. Selectivity of the fishing gears

Green crabs caught in the selectivity experiments were measured and grouped into CW classes of 2 mm. The mesh size selectivity of each gear was determined by comparing the number of crabs retained in each mesh size to the total number of individuals retained. Thus, for a given mesh size and size class, the proportion of crabs caught by each gear was calculated by taking the number of crabs (in the CW size class) caught by the tested mesh and dividing it by the total number of crabs caught, both in the gear and in the cover bag. These catch proportions were modelled using Millar's SELECT method (Share Each Length Class's Catch Total) to produce size selectivity models for box traps and drop nets (Millar, 1992).

Green crab size class data were assessed using the SELECT model, which applies both Logistic and Richard selection curves to the frequency data aggregated over each haul (Fig. 6). Residual plots and over-dispersion corrected quasi-likelihood ratio tests (Millar et al., 2004) identified the asymmetric Richards curve as the preferred model ($p < 0.001$) for all experiments. The SELECT model includes a parameter p, representing the conditional probability of a crab being caught by the specified gear, given that it is caught either in the gear or in the cover bag. Therefore, denoting this probability by p, the probability of a crab being retained by the non-selective cover bag is simply 1 less the probability of it be caught by the gear, i.e. 1-p. The following equation allowed us to calculate $r(w)$, which represents the probability of retention at size w, where 'a' and 'b' are parameters in the Richard curve equation. We estimated these parameters using the maximum likelihood approach described by Millar (1992).

$$r(w) = \frac{\exp(a + bw)}{1 + \exp(a + bw)}$$

The probability of a crab entering the gear and being retained in the gear can then be expressed as $p \times r(w)$. The total probability of a crab being retained by the gear or cover is the sum of these two probabilities, i.e., $(1-p) + p \times r(w)$. The SELECT model parameter estimates the W_{25}, W_{50}, W_{75} and SR, where W_{50} is the carapace width at which the probability of retention is 0.5. The SR is the selection range, i.e. the difference between W_{75} and W_{25}. Both W_{50} and SR values derived from the SELECT model have been used to describe and assess gear selectivity across fisheries and gears worldwide (Poirier et al., 2021). All the data analysis and visualisation was performed in the R SELFISHER R package (Brooks et al., 2020), which uses the SELECT model (Millar, 2021).

3. Results

3.1. Fishing gears and modus operandi

Two types of fishing gear are used in the Portuguese green crab fishery. In the Ria Aveiro, crabbers use drop nets, while in the Sado River and Ria Formosa, box traps are mainly used. In Ria Formosa, however, crabbers use both types of gear.

3.1.1. Box traps

3.1.1.1. Gear characteristics. Box traps have a rectangular shape with an iron frame and in some variations the bottom is slightly wider than the top (Table 1; Fig. 2). The frame is covered with stiff polypropylene netting of a specified mesh size. At the top, the trap has several entrances (funnels) to allow the crab to enter the trap and reach the bait. The number of entrances varies, and each trap also contains a bait container fixed at the top, with a 'door' where the bait is (re)placed. To remove crabs, the trap had a side door with a rubber seal attached to allow the door to open and close.

3.1.1.2. Modus operandi. Green crab box traps are usually static gears that operate for 24 hours. These gears are deployed in lagoons and estuaries near the banks, in shallow water between 1–2 m, rather than at the bottom of the channels, because crabs are mainly found in the intertidal zone and sometimes the gear remains dry at low tide (Fig. 2). Furthermore, setting traps in the middle of the channels is likely to result in them being overturned or lost due to stronger currents. Multiple traps linked by a rope can be deployed, or they can be deployed one by one. However, they are usually deployed individually to allow easier manoeuvrability between fishing areas depending on the catch. When deployed, the buoy attached to each trap indicates its position. Green crab fishing with box traps is carried out on board a fishing boat, which remains in constant motion while the gear is hauled, baited and set. If the crabbers wish to continue fishing, the traps are immediately rebaited and released.

3.1.2. Drop nets

3.1.2.1. Gear characteristics. Drop nets consist of a still-frame hoop that keeps the net open and not which a seine is sewn to hold the catch. The hoop is connected to a buoy by three lines that end in a single line used by the fisher to manoeuvre the gear. The bait is placed in a bait mesh bag attached to the hoop at the same level as the entrance of the hoop gear (details in Table 1; Fig. 3).

3.1.2.2. Modus operandi. This gear is deployed during the day near banks, as crabs are mainly found in these areas. The use of drop nets in the middle of channels often results in loss or overturning due to

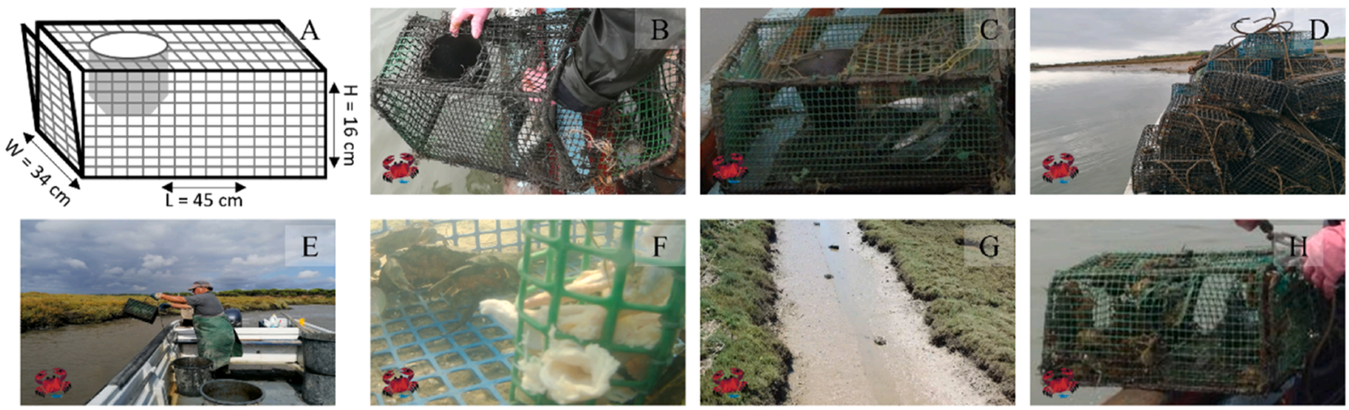

Fig. 2. Box trap - Fishing gear used in the crab fishery on Sado river and Ria Formosa. (A) schematic drawing of the drop net; (B and C) crabbers baiting the drop net; (D) Set of traps prepared to be deployed individually at regular intervals (E) fishing gear being deployed; (F) gear deployed and fishing using pork; (G) Box traps deployed webbed in the low tide. (H) gear being hauled, with the crab captured.

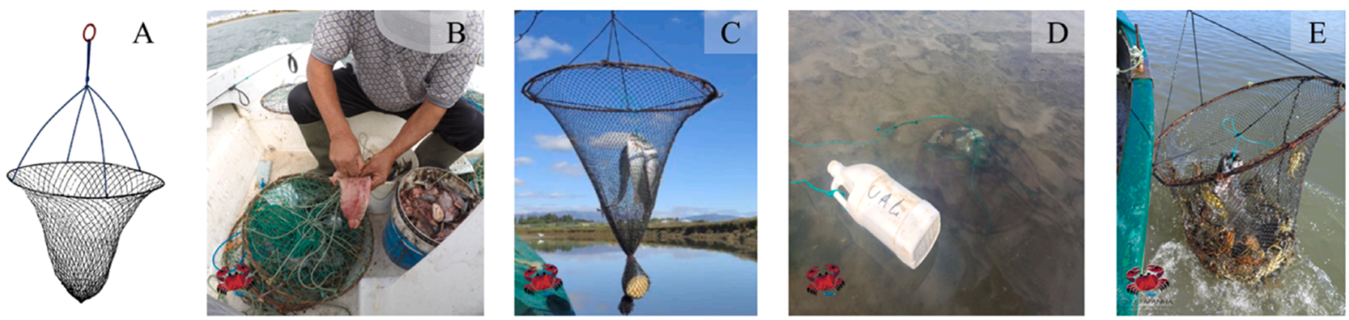

Fig. 3. Drop net - Fishing gear used in the crab fishery on Ria de Aveiro and Ria Formosa. (A) schematic drawing of the drop net; (B) crabber baiting the drop net; (C) fishing gear in a field trip ready to be deployed; (D) gear deployed and fishing; (E) gear being hauled, with the *Carcinus maenas* captured.

currents. This fishery is carried out by boat and the drop nets are set individually at regular intervals. The net and the iron hoop remain in horizontal contact with the bottom during soaking, and the buoy indicates its position. Fishing with drop nets is fast paced, with crabbers setting out 10 to 15 drop nets in a row and each one remains fishing for an average of 15–30 minutes (Fig. 3). The use of 10 to 15 drop nets means that when the crabbers reach the last gear, they can wait a few minutes before starting to raise the gears in the deployment order. Gear is hauled quickly after a short jig to avoid crabs running out of the gear/hoop and forcing them to fall into the net bag.

3.1.3. *Fishing bait type*

In Portugal, different types of bait are used in the green crab fishery. Crabbers are not restricted to using a single type of bait i.e., their choice depends on the availability and economic price of the bait. The most used baits are small and medium pelagics, such as chub mackerel (*Scomber colias*), mullet (family *Mugilidae*), and horse mackerel (*Trachurus trachurus*).

In the Ria de Aveiro and the Sado River, crabbers use only fish as bait. In contrast, in the Ria Formosa, a wider range of bait is used, including chub mackerel (45 %), mullet (15 %). horse mackerel (13 %), seabreams (*Boops boops*) (12 %), pork and chicken scraps (6 %), Sardines (*Sardina pilchardus*) (3 %) and various fish scraps (6 %) including fish and octopus guts, black scabbardfish heads or bivalves such as cockles.

3.2. *Fishery catches*

Catch per unit of effort per gear (CPUE-gear) varied between systems (Fig. 4 A) (one-way ANOVA: F= 22.91; *p-value* < 0.001). Sado river was the system with the highest CPUE-gear. However, in Sado river, crabbers used only box traps. In Ria Formosa, both gears were used, but the CPUE-gear was lower compared to Ria de Aveiro (drop nets) and Sado river (box traps). Statistical differences were observed between the CPUE-gear of box traps in Sado River and Ria Formosa (T-test: Z = 1061.09; *p-value* < 0.001). In the Sado River, a 24-hour deployment catches 3 kg of green crab per trap, whereas in the Ria Formosa, the CPUE-gear is lower (0.5 kg trap/day). A similar pattern is observed with drop nets, with statistical differences observed between the CPUE-gear in Ria de Aveiro and Ria Formosa (T-test: Z = 188.86; *p-value* $<$ 0.001). In Ria de Aveiro, a 30-minute operation with a drop net catch 1 kg/30 min of green crab, while in Ria Formosa, the CPUE-gear is much lower, around 0.120 kg/30 min.

On a fishing day (Fig. 5B), when crabbers use 40 box traps or 150 drop nets (15 drop nets for 5 hours) (CPUE-day), no statistical differences were observed in the total catches of the crabbers between gears (T-test: Z = 15.46; *p-value* = 0.876). However, the CPUE-day varied between systems (T-test: Z = 1133.76; p-value < 0.001) (Fig. 4B). In the Sado River, the crabber has an average catch of 130 kg, while in the Ria Formosa, the average catch is around 30 kg. The same pattern was observed with drop nets, there were statistical differences in CPUE-day between Ria de Aveiro and Ria Formosa (T-test: Z = 1497.45; *p-value* $<$ 0.001). In Ria de Aveiro, a crabber can catch about 150 kg of crabs in one fishing day (working 5 hours), while in Ria Formosa only 20 kg can be caught.

Regardless of the gear, CPUE-day varied both intra- and interannually (Fig. 4 C), indicating that both year and month have significant effects on daily catch (Box traps: Two-way ANOVA: F= 14.15; *p-value* $<$ 0.001; Drop nets: Two-way ANOVA: F= 3.32; *p-value* < 0.001). For box traps (Sado River), a positive statistical correlation was observed between temperature (SST) and CPUE-day (Pearson correlation: R = 0.120; p-value $<$ 0.001) over months, with the highest CPUE-day

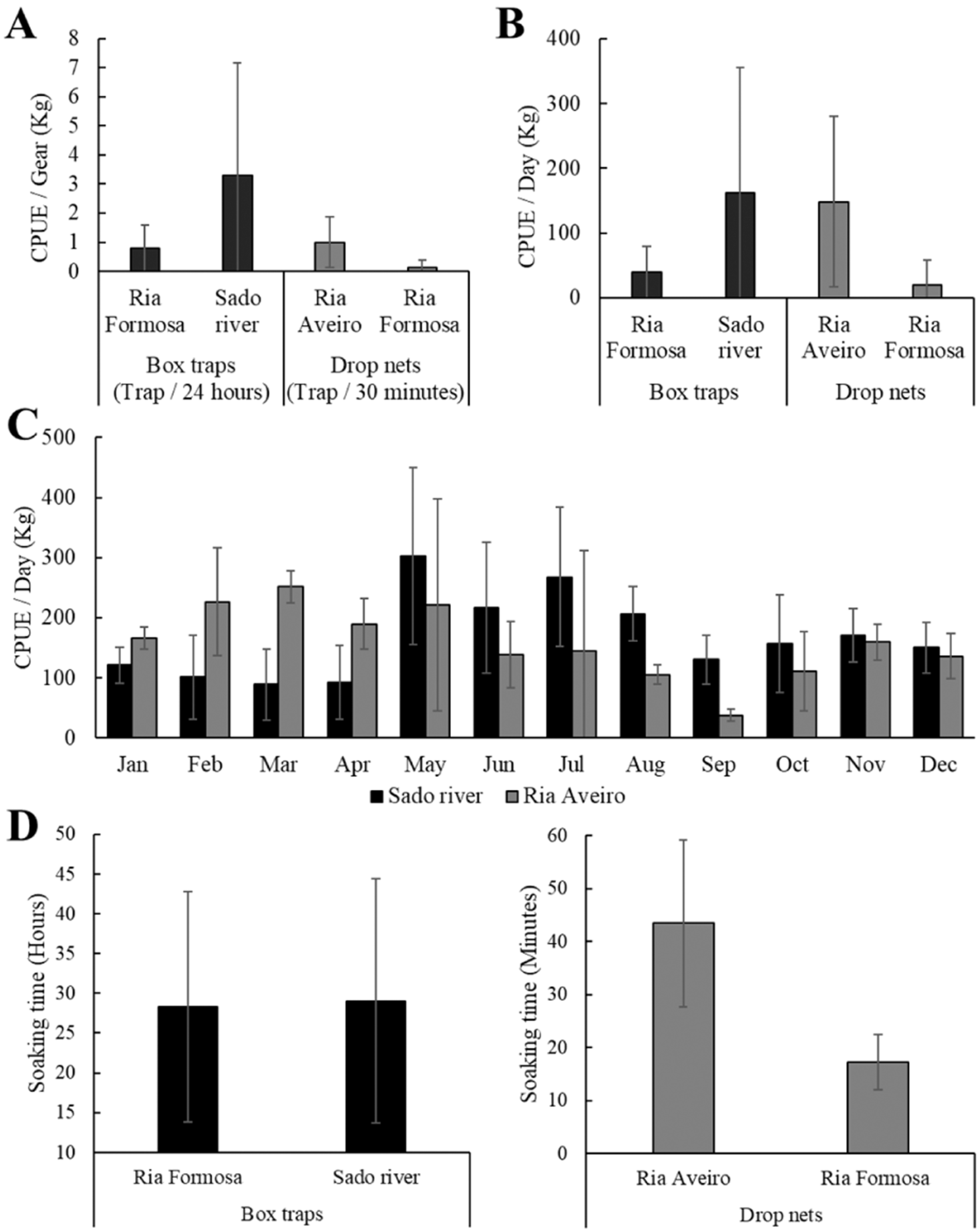

Fig. 4. Characterisation of green crab fishing operations and catches with both fishing gears in three Portuguese lagoon/estuarine systems. (A) Catch per unit of effort per gear (CPUE-gear) with box traps and drop nets; (B) Catch per unit of effort per day (CPUE-day) with box traps and drop nets (40 box traps per day, and 150 drop nets per 5 hours working in a day); (C) Catch per unit of effort per day (CPUE-day) with box traps and drop nets over months in Sado river and Ria Aveiro; (D) Fishing effort of both fishing gears, box traps in hours and drop nets in minutes.

occurring in warmer months, particularly in May and September. In contrast, a negative statistical correlation was observed between temperature (SST) and CPUE-day (Pearson correlation: $R = -0.312$; p-value < 0.001) over months for drop nets (Ria Aveiro). A decrease in CPUE-day was observed with drop nets in warmer months (May to September), and the highest CPUE-day was observed in colder months (November to April).

Fishing effort (soaking time) of both fishing gears varied between systems (Fig. 4D). The average effort recorded for traps was 28 hours for both systems, and for drop nets the maximum soaking time was 1 hour, with an average of around 40 minutes in the Ria de Aveiro and 15 minutes in the Ria Formosa. Statistical differences were observed between the soaking times for both fishing gears, between the systems (Box traps T-test: $Z = 16.43$: *p-value* < 0.001; and Drop nets T-test: $Z = 155.64$; *p-value* < 0.001).

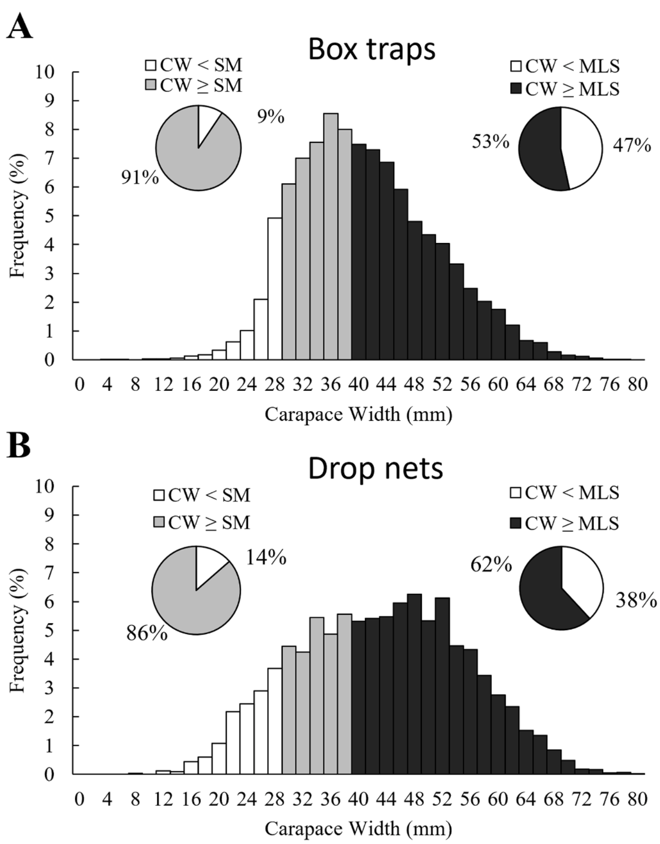

Fig. 5. Size-frequency distribution of catches with box traps of 18 mm of mesh size (A) and drop nets of 30 mm of mesh size (B) in the Portuguese systems. White is the proportion of individuals below the minimum landing size (MLS) (40 mm carapace width) and size at maturation (SM) (30 mm carapace width) established for *Carcinus maenas*. Black and grey are the proportions of individuals above the MLS and SM.

3.3. Green crab size composition and by-catch species

The size-frequency distribution of the target species (*C. maenas*) with the proportion of individuals below and above the size at maturation (SM, 30 mm of CW) and minimum landing size (MLS, 40 mm of CW) is shown in Fig. 6. Crabs caught in the box trap ranged in size from 12 to 78 mm CW and in drop nets from 12 to 81 mm of CW. During the field samplings, both gears caught specimens with a wide size range and with a high proportion of undersized individuals relative to the MLS. Specifically, 47 % of the specimens caught with box traps (Fig. 5 A) and 38 % with drop nets (Fig. 5B) were undersized when using mesh sizes of 18 mm and 30 mm, respectively. However, when considering the size at maturation, the percentage of undersized individuals was 9 and 14 %, respectively. Furthermore, statistical differences in the CW class frequency distribution were observed between the two fishing gears (two-samples KS test: Z = 8.968, *p-value* < 0.001).

It was found that drop nets did not retain any by-catch. The taxonomic identification and abundance of the by-catch species caught in box traps are summarised in Table 2. A total of 560 by-catch specimens belonging to 16 taxa were caught, with gastropods comprising most by-catch (57.7 % of the by-catch) due to high abundance of sea snails (*Tritia spp.*) (7.89 ± 4.99 individuals per 40 traps) and *Steromphala umbilicalis* (with 3.69 ± 3.75 individuals per 40 traps). Several specimens of other taxonomic groups belonging to the phyla Arthropoda and Chordata were also caught, with Arthropoda being the most abundant group (35.7 % of the by-catch), mainly due to the African mud crab *Panopeus africanus* (7.93 ± 10.48 individuals per 40 traps) (Table 2).

Comparison of the total number of target species and by-catch species caught in box traps during the experimental fisheries showed that the target species accounted for over 99 % of the total catch by weight, with by-catch species accounting for less than 1 % of the total catch in weight. No statistical correlation was observed between daily total catches of green crab and by-catch (Pearson correlation: R= 0.17; *p-value* = 0.63), and between green crab catches and temperature (Pearson correlation: R= −0.13; *p-value* = 0.69) over months. Monthly total catches of the target and by-catch species were highly variable during the study period, with no clear monthly pattern (Fig. 6). The highest by-catch catches in weight occurred during the warmest months (July, August and September). A correlation between by-catch and temperature was observed (Pearson correlation: R= 0.58; *p-value* = 0.05).

3.4. Selectivity of the fishing gears

The CW_{50} estimated for box traps with mesh sizes of 8, 18, and 30 mm were 14.10 mm, 29.04 mm, and 50.03 mm CW respectively and the selectivity ranges were 0.18 mm, 1.02 mm, and 2.14 mm respectively (Fig. 7; Table 3). The estimated CW_{50} for 30, 40 and 50 mm drop nets with mesh sizes of drop nets were 27.69 mm, 45.02 mm and 45.91 mm CW respectively and the selectivity ranges were 1.97 mm, 7.41 mm and 6.65 mm respectively (Fig. 7; Table 3). At a minimum landing size (MLS) of 40 mm, retention probabilities using box traps of mesh sizes 8, 18 and 30 mm were 100 %, 100 % and 0 % respectively. The retention probabilities at MLS using drop nets of mesh size 30, 40 and 50 mm were 100 %, 40 % and 12 % respectively. In addition, at size at maturation (SM) of 30 mm, the retention probabilities of crabs using box traps of mesh size 8, 18, and 30 mm were 100 %, 89 %, and 0 %, respectively. The retention probabilities at SM using drop nets of mesh size 30, 40, and 50 mm were 93 %, 3 %, and 1 %, respectively.

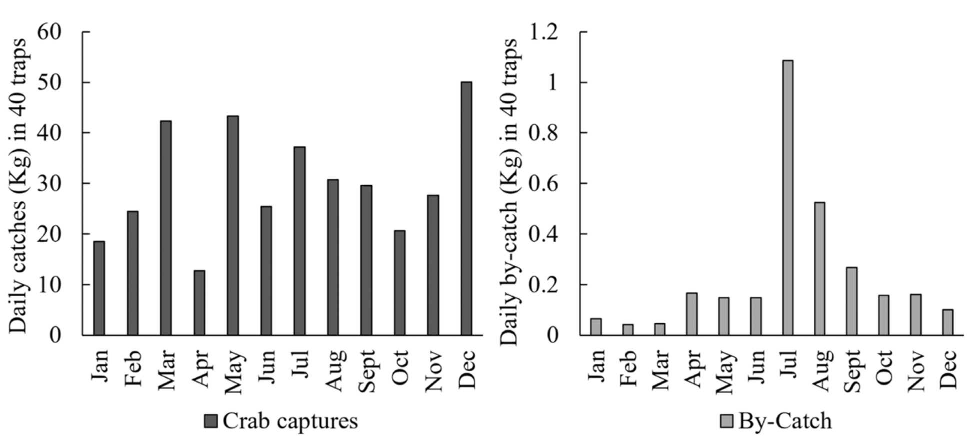

Fig. 6. Daily catches of green crab (left) and by-catch (right) in kg per month in Ria Formosa, with 40 box traps with a mesh size of 18 mm.

Table 2
Taxonomic identification with number of individuals and weight of by-catch species. Values are mean number and weight (± standard deviation) by fishing day with 40 box traps.

Taxa	Nº of Individuals	Weight (g.)	Taxa	Nº of Individuals	Weight (g.)
Phylum Arthorpoda			Phylum Mollusca		
Class Malacostraca			Class Bivalvia		
Order Decapoda			*Polititapes aureus*	0.17 ± 0.44	0.95 ± 2.46
Family Diogenidae			Class Cephalopoda		
Clibanarius erythropus	0.04 ± 0.15	0.20 ± 0.76	*Octopus vulgaris*	0.08 ± 0.31	16.41 ± 61.40
Family Eriphiidae			Class Gastropoda		
Eriphia verrucosa	0.34 ± 0.65	28.64 ± 56.35	Order Caenogastropoda		
Family Majudae			*Bittium reticulattum*	1.80 ± 1.06	2.75 ± 1.53
Maja squinado	0.04 ± 0.16	1.06 ± 3.96	Order Neogastropoda		
Family Ocypodidae			Family Columbellidae		
Afruca tangeri	0.11 ± 0.30	1.68 ± 4.57	*Columbella rustica*	0.04 ± 0.15	0.32 ± 1.19
Family Panopeidae			Family Muricidae		
Panopeus africanus	7.93 ± 10.48	90.06 ± 117.23	*Hexaplex trunculus*	0.17 ± 0.36	4.05 ± 8.25
Phylum Cordata			Family Nassariidae		
Class Actinopterygii			*Tritia spp.*	7.89 ± 4.99	30.13 ± 81.16
Family Labridae			Order Trochida		
Symphodus bailloni	0.17 ± 0.35	5.42 ± 11.13	*Steromphala umbilicalis*	3.69 ± 3.75	5.19 ± 5.22
Family Mugilidae			Total	23.60 ± 11.79	214.32 ± 257.11
Chelon ramada	0.04 ± 0.15	0.80 ± 2.98			
Family Sparidae					
Diplodus spp.	1.06 ± 1.94	25.01 ± 46.16			
Family Scorpaenidae					
Scorpaena sp.	0.04 ± 0.14	1.67 ± 6.24			

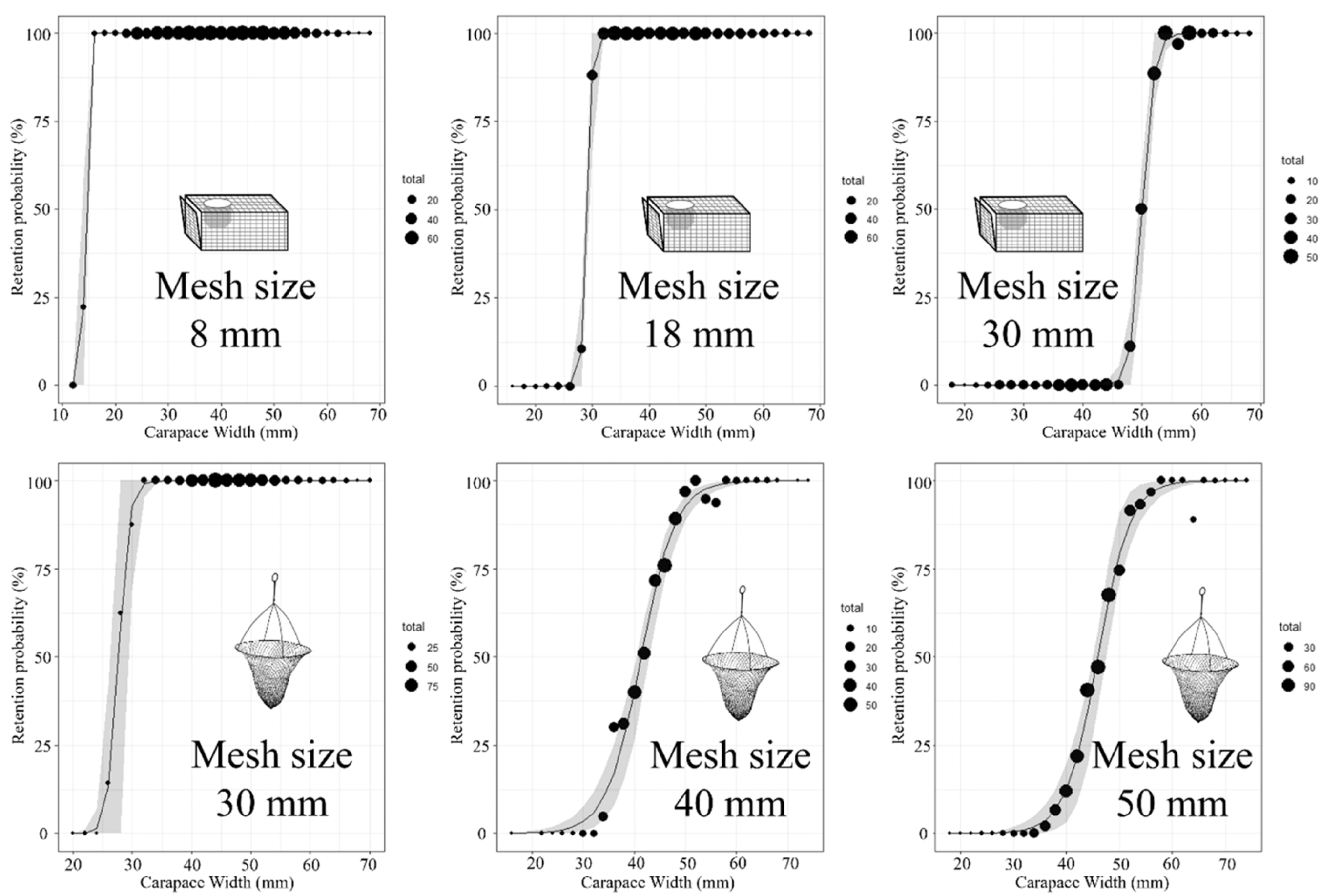

Fig. 7. Selectivity curves, based on Richards curve SELECT models, for each gear used in the Portuguese green crab fishery. For each gear it was tested three different mesh sizes 8, 18 and 30 mm of mesh size for the box traps (upper graphs), and 30, 40 and 50 mm of mesh size for the drop nets (bottom graphs).

4. Discussion

Carcinus maenas fishing remains poorly understood in its native region, with very few studies analysing this fishery (Gomes, 1991; Sheehan et al., 2008). In Portugal, green crab fishing has been conducted in most of the Portuguese lagoon and estuarine systems since 1950 (Leitão and Monteiro, 2022), but scientific knowledge of this fishery is scarce. Overall, this study provided new insights into the green crab

Table 3
Green crabs (*Carcinus maenas*) carapace width (CW) (mm) retention probability and selectivity range for the three-mesh sizes for both fishing gears (box trap and drop nets).

Gear	Mesh size (mm)	Retention probability (CW in mm)			Selectivity Range (CW in mm)
		25 %	50 %	75 %	
Box trap	#8	14.01	14.10	14.19	0.18
	#18	28.52	29.04	29.55	1.02
	#30	48.96	50.03	51.10	2.14
Drop net	#30	26.70	27.69	28.67	1.97
	#40	37.61	41.32	45.02	7.41
	#50	42.59	45.91	49.24	6.65

fishery in the native region by analysing the main characteristics and *modus operandi* of the fishing gear, bait used, catch per unit of effort (CPUE), total daily catches, fishing effort, carapace width frequency of crab catches, as well as by-catch for both gears used in the crab fishery. In addition, the mesh size selectivity of the fishing gears used in the Portuguese green crab fishery was analysed for the regulation based on minimum landing size (MLS) and/or biological size at maturity (SM).

Fishing gears used in Portugal differs from that used in North American fisheries (McKenzie et al., 2022). North American fisheries use different types of fishing gear (Young et al., 2017; McKenzie et al., 2022), many of which are similar to Portuguese box traps but not drop nets. Box traps are typical artisanal fishing gears, characterised by a high variability in their dimensions and specific components (main lines and shapes). According to the available literature the most common box traps in North America are the Fukui traps (Bergshoeff et al., 2019; Favaro et al., 2020) and the 'Ketcham' traps (Young et al., 2017). A previous study in Massachusetts, USA, evaluated several box traps used when fishing for green crab and observed differences in CPUE between them (see Young et al., 2017 for details). The box traps used in Portugal are similar to the 'Ketcham' traps analysed in Young et al. (2017). These traps are relatively small and can be easily transported and hauled, as shown in Fig. 4. This allows crabbers to use a large number of traps per day. However, due to their small size, these traps are not suitable for use in waters with strong currents and typically result in lower CPUE compared to larger and heavier box traps (Young et al., 2017).

Cost-effectiveness of baits in fisheries is crucial for maintaining the profitability and sustainability of fisheries (Patanasatienkul et al., 2020; Leitão et al., 2023). Economically viable bait options not only reduce operational costs for fishers, but also minimise the overall environmental impact, ensuring the long-term health and viability of marine ecosystems (St-Hilaire et al., 2016; Leitão et al., 2023). In the *C. maenas* fishery, this is not a concern for crabbers, as *C. maenas* has an omnivorous and non-selective diet when food is scarce (MacDonald et al., 2018). Portuguese crabbers bait choice depends mostly on the availability of bait from fish markets at minimal or no cost. In this study, we did not compare fishing yields based on the type of bait used. However, previous studies have shown that the type of bait influences the catch of *C. maenas* (Young et al., 2017). Herring has previously been identified as one of the best baits for the *C. maenas* fishery, as herring is an abundant species (and therefore cheap) and is an oily fish, which allows it to effectively attract crabs (Young et al., 2017). In Portugal, Atlantic chub mackerel (*Scomber colias*) replaces herring as the most common bait because it is also an oily fish, very abundant and has a low market cost (Erzini et al., 2003), which improves the cost-effectiveness of the traps. In addition, some crabbers catch their own bait, such as the Sado River crabbers who catch mullets specifically to use as bait for the green crab fishery. Another example can be found in the southern region of Portugal, where the high value of fish bait has led crabbers to also use pork and chicken scraps which they acquired at local markets at no cost. This represents a circular economy (no waste) and an intelligent fishery adaptation to climate change, where no additional greenhouse gas emissions (GHG) are generated for acquired waste-bait.

The *C. maenas* fishery in Portugal is almost unknown and therefore the local ecological knowledge (LEK) of crabbers is a major asset to understand the fishery (Cosham et al., 2016; Obregón et al., 2022), such as the fishing gear *modus operandi* and the variation of CPUE among gears, months and regions. CPUE varied between gears, box traps are static gears that fish for 24 hours and the probability of green crab escape is minimal and only occurs when the capacity of the trap is saturated (Young et al., 2017). In contrast, drop nets fish for short periods of time (30 minutes on average) and crabs are quickly attracted to the gear. However, unlike box traps, crabs can escape as the net is dropped into the bottom, aligning horizontally with the seabed. Both fishing gears have their advantages and disadvantages (see Supplementary Information Fig. S1 for a summary); box traps have a higher CPUE-gear, low bait consumption, low environmental impact and require less manpower. However, the use of minimum mesh sizes to target crabs remains unregulated, posing a threat to fishers using this gear. In addition, box traps are only hauled once a day and the onboard storage of box traps is more difficult, making rotation between fishing areas difficult. One of the main advantages of drop nets is that, despite the lower CPUE-gear compared to box traps, drop nets can be used several times within the same fishing day. Therefore, if crabbers work with drop nets for more than 5 hours, the daily catch with drop nets will be greater, but it will also require more labour and time in the fishery. Drop nets also allow crabbers to change fishing grounds if a particular area does not allow fishers to attain satisfactory catches, as they are easy to store on board and are more manoeuvrable than box traps. However, there are disadvantages to drop nets. For example, bait and fuel consumption is higher than with box traps and drop nets are more likely to overturn (no catch) and to lose gear in strong currents than box traps.

Local Ecological Knowledge of the crabbers obtained during the field sampling indicates that the daily abundance of green crabs in catches varies according to the month and the fishing gear used. Drop nets and box traps are two types of fishing gear with different characteristics and fishing procedures. These differences result in different daily catch trends throughout the year, with the observed variation between the two gears being inverse. Box traps yield higher catches in warmer months, while drop nets are more effective in colder months. These results can be explained by the behaviour of *C. maenas* throughout the year. In the colder months, between September and April, crabs are more active and increase their foraging activity, so drop nets yield higher catches than box traps, as attraction to drop nets by the bait odour implies a slight sequence of crab behavioural activities compared to box traps (bait accessibility is easy for crabs in drop nets). In box traps, crabs are forced to climb to the top of the trap and enter the trap where they are retained until the gear is hauled. Conversely, in warmer months, when green crabs are less active and buried (Young and Elliott, 2020), drop nets result in lower daily catches because the time the gear remains soaked is not enough to attract crabs, leading fishers to constantly search for fishing grounds with higher crab abundance. As box traps remain in the water for a longer period (24 hours), there is a greater chance of catching more crabs in the summer compared to traps. Therefore, seasonal gear rotation could be used to increase catches and maximise fishermen's income.

Another interesting feature demonstrated in this study is the LEK of crabbers regarding the crab fishing regulations enforced in Portugal. Crabbers indicated that the minimum landing size (MLS) was extremely high (Leitão and Monteiro, 2022). However, this was revised in 2023 and the MLS was reduced from the previous 50 mm carapace width (CW) to the current 40 mm CW (Portaria nº 255/2022). However, the MLS remains high considering that *C. maenas* reaches sexual maturity at 30 mm CW, as reported by Souza et al. (2011) for the Minho estuary (North) and by Monteiro et al. (2025) for the Ria de Aveiro (North), Sado river (Centre), Ria Alvor (South) and Ria Formosa (South). In Portugal, drop nets have been used since the beginning of the green crab fishery (mid-20th century), while the use of box traps started more recently (Leitão and Monteiro, 2022). The box traps are not regulated and characteristics of the gear, including mesh size, are adapted to octopus or cuttlefish fishing in lagoons and estuaries and not to crab fishing/biology. Therefore, we developed mesh size selectivity experiments to determine the mesh size required to select crabs based on the MLS and size at maturity, which allows them to spawn at least once prior to capture.

In the selectivity experiments, it was observed that the perception of crabbers is accurate; under the current law, catches with the mesh size allowed for box traps (30 mm mesh) resulted in low income and only green crabs with a CW greater than 50 mm were caught. The mesh size of 18 mm allows to achieve a higher income with catch being comprised crabs larger than the size at maturation (SM) of 30 mm CW (Souza et al., 2011; Leitão and Monteiro, 2022). The smallest mesh size tested (8 mm) showed that many crabs below the size at maturation were caught. Therefore, based on results it is proposed for crab fishery regulation a 18 mm mesh size for box traps. For drop nets the 30 mm mesh size can be enforced for *C. maenas* fisheries, as most crabs caught with this mesh size are above SM (30 mm of CW). Regardless of the enforced MLS, it is necessary to sieve the excess of crabs below the MLS (40 mm) after fishing for both gears. In the Ria de Aveiro and Sado river, the fishers sort the crabs with an iron grid sieve, which allows the crabs to be sorted according to the thickness of the carapace. The space between the bars of the grid, which allows the crabs to be sorted according to MLS (40 mm) and SM (30 mm) is 17 mm and 13.5 mm respectively (Leitão and Monteiro, 2022). Sorting should be carried out on board in order to discard undersized crabs in the same/nearest fishing beds, thus avoiding desiccation or redistribution to unsuitable areas and reducing indirect fishing mortality.

In contrast to other fisheries, the gear used in green crab fisheries is species selective and promotes the live release of by-catch (Suuronen et al., 2012; Poirier et al., 2018). The low by-catch in the crab fishery is consistent with previous studies analysing *C. maenas* fishery in North America, where by-catch has always been considered minimal and the majority of by-catch species consisted of other native crab species (Tremblay et al., 2006; Bergshoeff et al., 2019; Favaro et al., 2020). Although the fishing gears are not fully size-selective, they are species-specific selective, as observed by the number/weight of by-catch caught during the experiments for both fishing gears. In our study, we observed that catches of other crab species were low. However, this result was expected, as *C. maenas* is the most abundant estuarine crab in Portugal (Monteiro et al., 2025), in contrast to non-native regions where there are various crabs with morphological and behavioural characteristics similar to *C. maenas* (Bergshoeff et al., 2019).

By-catch in box traps consists mainly of sea snails of the genus *Tritia* and the mud crab, *Panopeus africanus*. Sea snails are quickly discarded into the lagoon during fishing, however, *P. africanus*, due to low amounts, is caught and sold together with the *C. maenas* specimens. Results showed no relationship between *C. maenas* catches and by-catch species (weight), but by-catch was affected by water temperature. In the warmer months (July to September), *P. africanus* specimens increase their activity and become more abundant, corresponding to the reproductive season of this species (Monteiro et al., 2024b) and the months when by-catch was higher. With drop nets, all non-target and unwanted fauna are removed after fishers lift and shake the gear directly to the sea. The environmental impact and the direct or indirect mortality resulting from the use of drop nets can be at ecological level considered for habitat and to benthic community negligible. Thus, both fishing gears used in *C. maenas* fishery have a low impact on the non-target invertebrate and fish communities.

There is potential for the sustainable development of green crab fisheries in estuaries in Europe, namely in Portugal. This will allow us to reduce the pressure on the overexploited traditional fishery resources and to explore different applications of the green crab, including the use as seafood, as it is already explored in North America and even in some areas of Europe, namely Italy (Young and Elliott, 2020). Most estuarine fishers focus their activities on green crab fishing during certain periods of the year as an alternative and secondary source of income. However, crabbers' request fisheries authorities to regulate box traps to target only on crabs, but the fishery remains unregulated due to the lack of gear size selectivity studies and environmental studies (Leitão and Monteiro, 2022). Therefore, there is now an opportunity to regulate this fishery taking into account the results of this study. Families with historical fishing rights, such as those using drop nets, can benefit from licences to operate with both types of gear.

The study of technical gear selectivity issues, fishing yields and ecological impacts of gear is essential for better management in poorly science-based regulated fisheries. Fisheries biology and ecology studies could be used to introduce output and input fisheries management controls, as observed in other crab fisheries (MacKenzie and Cox, 2013; Bellido et al., 2020; Willse et al., 2024). Although *C. maenas* landings have never exceeded maximum sustainable yields (Monteiro et al., 2024a), the green crab fishery requires regulatory updates. Both gears have lower by-catch and therefore lower environmental impacts at the ecological conservation level. Input controls may include limiting fishing licences and the number of gears per boat. Output controls may include updating the minimum landing size (Monteiro et al., 2025) and, as in other crustacean fisheries, discarding ovigerous females (Bellido et al., 2020; Willse et al., 2024). In addition, if the green crab fishery in Portugal grows, daily bag limits and closed seasons could also be enforced.

5. Main conclusions

Ecological impact of fishing gears used in the Portuguese green crab fishery was characterised and best gear mesh size was determined in order to adapt gear selectivity to green crab reproduction biology. The results showed that two different types of fishing gear are used in the *C. maenas* fishery in Portugal, both of which have a low environmental impact. According to the current minimum landing size (40 mm of carapace width) and size at maturation (30 mm), the commonly used mesh sizes of 18 mm in box traps and 30 mm in drop nets allow a reduction of undersized specimens while maximising catch rates. Regardless of the gear used, crabbers must screen their catches. For this purpose, the sieve bar spacing, which allows sorting of green crabs according to minimum landing size and size at maturation, should be set at 17 mm and 13.5 mm respectively. It was observed that different types of bait are used and that catches varied considerably both between months and years. The baseline information gathered in this study, complemented by relevant aspects of the biology of *C. maenas*, such as growth and reproductive cycles, will allow the proposal of fishery management measures, including the regulation of box traps for the exclusive capture of crabs in Portuguese estuaries. In addition, this study could be used as a model that combine technical gear selectivity issues, fishing yields and gear ecological impact in order to guide sustainability in fisheries.

CRediT authorship contribution statement

Leitão Francisco: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Teodósio Maria Alexandra:** Writing – review & editing, Validation, Methodology, Funding acquisition. **Ovelheiro Andreia:** Writing – review & editing, Investigation. **Monteiro João Nuno:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis.

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 paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107284.

Data availability

Data will be made available on request.

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