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Research Article

An experimental approach to non-indigenous species management: testing the selectivity and capture efficiency of thick trammel nets for lionfish *Pterois miles* in the southern Aegean of Türkiye

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Abstract

Managing non-indigenous species (NIS) is a key priority for natural resources managers, particularly as climate change increases the risk of these species becoming invasive. The lionfish (*Pterois miles*), an invasive NIS in the eastern Mediterranean and southern Aegean seas of Türkiye, has become a target for small-scale fishers (SSF) due to declining native fish stocks and NIS control efforts. A market-based approach to exploiting lionfish is a promising strategy, given the challenge of complete eradication in marine ecosystems – even though its commodification may carry unintended ecological and socio-economic risks in the long term. In Türkiye, despite market demand, fishers hesitate to supply lionfish due to potential gear damage and safe handling. This study examines the size selectivity and catch efficiency of thick trammel nets (TTNs), commonly used by SSF in Türkiye to overcome this barrier. Fishing trials from 2022 to 2024 mainly in the summer using TTNs with varying mesh sizes in the southern Aegean Sea caught 771 lionfish (18.2–42.7 cm total length). Results showed significant differences in mean total lengths across mesh sizes, with optimal model lengths exceeding the species' first maturity length (L_{50}). Larger mesh sizes may meet market demand but are insufficient for population control, while smaller mesh sizes have an increased risk of bycatch of native species. Nevertheless, since TTNs generally have limited bottom contact compared to more destructive gear types such as trawlers and purse seiners, defining an optimal mesh size targeting lionfish has been the main aim of this study to inform decision-makers and SSF on best means available to tackle lionfish invasion in a collaborative way.

Key words: fisheries management, safe handling, invasive species, fishing gear, adaptive management

Introduction

Non-indigenous species (NIS) are organisms introduced outside their native range, typically through human activities. While many remain benign, some become invasive, causing ecological or economic harm (Pasko and Goldberg 2014; Soto et al. 2024). Beyond ecological threats, invasive species such as *Pterois miles* also impose substantial economic

costs, yet these impacts have been largely overlooked in risk and impact assessments (Soto et al. 2023). In this context, the management of NIS requires a multidisciplinary approach that considers not only their ecological impacts and interspecies interactions, but also their socio-economic consequences – including monetary costs (Ünal et al. 2015; Öndes et al. 2018; Azzurro et al. 2024). Therefore, effective long-term management of NIS demands an integrated approach that is financially viable, cost-efficient, socially acceptable and environmentally sound (Chapman et al. 2016).

The term NIS is used throughout this study in accordance with the terminology commonly adopted by international organizations such as the Food and Agriculture Organization (FAO) and the General Fisheries Commission for the Mediterranean (GFCM), particularly in regional monitoring and management frameworks (Öztürk 2021). Although some species like the *Pterois miles* (hereafter "lionfish") are widely recognized as invasive due to their ecological impacts (Bottacini et al. 2024) the broader term NIS is maintained to ensure consistency with policy and reporting conventions. Recent discussions in invasion science have highlighted the need for more impact-based classifications (e.g., Soto et al. 2024), which are relevant for interpreting the ecological and socio-economic dimensions of NIS.

The common pathways for marine NIS introduction in the Mediterranean include ballast water from ships, aquaculture and marine trade (Occhipinti-Ambrogi and Savini 2003; Ruiz et al. 2000). To date, almost 500 marine alien species have been identified on Türkiye's coast (Çınar et al. 2021). Since the expansion of the Suez Canal, completed in 2016, rapid increase in the number of NIS have been recorded in Turkish waters. In the southern Aegean Sea, species like the lionfish, silver toadfish (*Lagocephalus sceleratus*), redcoat (*Sargocentron rubrum*) and rabbitfish (*Siganus rivulatus* and *S. luridus*) are among the most prominent examples.

Among these NIS respectively a recent invasion led by lionfish has been on the frontline in the Mediterranean. This species has even been spotted in Italian waters, as reported in southern Sicily in 2016 (Azzurro et al. 2017). Lionfish can cause significant ecological damage within their invaded range (Morris et al. 2012; Ulman et al. 2022). Reproduction of lionfish is particularly prolific, contributing to their rapid population growth and invasion success. They can reproduce year-round, with females releasing batches of up to 30,000 eggs every few days (Morris and Whitfield 2009). High fecundity and frequent spawning cycles enable lionfish populations to expand swiftly, overwhelming native ecosystems (del Río et al. 2023). This reproductive efficiency, coupled with their resistance to parasites and lack of natural predators, facilitates their establishment and persistence in new habitats (Fogg et al. 2017). In addition, their broad diet and novel foraging techniques allow them to prey on a wide variety of native species,

leading to a reduction in biodiversity (Savva et al. 2020). These factors disrupt ecological processes and create imbalances in the habitat, negatively impacting native species and the overall health of the ecosystem.

Biological invasions in the Mediterranean Sea have resulted in substantial biogeographic changes, shifts in the ranges of native species, population declines and, in some instances, even local extinctions (Katsanevakis et al. 2014).

In line with these strategic policy directions and ecological imperatives, various studies have explored practical removal methods to manage invasive lionfish populations. There have been several studies to date, on fishing gear trials targeting lionfish. One of the most effective removal methods has been spearfishing in the Atlantic (Akins 2012). However, this approach has limitations, as it can only be applied in areas divers can easily access, making it ineffective for widespread use as a large-scale fishing method (Gittings et al. 2017).

According to a review study by Farquhar (2017), spearfishing dominates lionfish removal in the Atlantic (45%), but is depth and diver limited. Other gears such as hand nets, traps, lines remain undertested in the Mediterranean, highlighting the need for scalable trials of TTNs. Only one survey study has been conducted on the rates of lionfish encounters by gear type in the eastern Mediterranean. Although a total of 93 fishermen were surveyed in the study, only 29 (31%) reported lionfish catch. Demersal trawling was the most frequently reported method (67%), followed by nets and seines (39 and 33%, respectively), longlines (25%) and spear guns (17%). Anglers had the lowest rate of catch (11%) (Özbek et al. 2017).

Modified Gittings traps, adapted from Atlantic use, were tested along Türkiye's southwestern coast but showed low effectiveness (Gittings et al. 2017; Harris et al. 2020; Tosunoğlu et al. 2025). This suggests the importance of developing removal methods tailored to local conditions.

Apart from commercial fishing methods, recreational fishing activities have recently been organized to spear lionfish in the eastern Mediterranean (Ulman et al. 2022).

Bounty programmes or subsidies represent a potential strategy to manage NIS populations, as demonstrated by current efforts targeting pufferfish species (primarily *Lagocephalus sceleratus*) in Türkiye. In this case, the Ministry of Agriculture and Forestry provides financial incentives to SSF for each individual caught, aiming to reduce the population through targeted removals (Official Gazette 2024). However, despite the increasing spread and ecological impact of lionfish, no similar government-led bounty or support programme has ever been existed for this species in Türkiye. Efforts to control lionfish populations focus on the active capture and consumption of lionfish primarily led by NGOs. Initially, fishermen and the public had limited information about lionfish in Türkiye. In 2020, approximately 100 kg of lionfish were caught each day in a 2000 m length of 60 mm small mesh size thick trammel nets (TTNs) in Kaş-Kalkan

fishing area. However, the risk of injuries caused by the venomous spines and difficulty of removing lionfish from these small-mesh nets caused fishermen to stop targeting lionfish (Tosunoğlu et al. 2025). However, due to promotional efforts by a couple of NGOs and the government, lionfish are increasingly appearing in restaurants and are becoming popular among consumers, leading to an increase in demand (Kok et al. 2022; Tosunoğlu et al. 2025). In Türkiye, lionfish has begun to gain market value, reflected in a notable increase in reported landings. According to official marine fisheries statistics published by the Ministry of Agriculture and Forestry and the Turkish Statistical Institute (TÜİK), the annual catch of lionfish rose from 3 tonnes in 2023 to 13 tonnes in 2024 (TÜİK 2025). This upward trend suggests growing consumer demand and increased targeting of the species by fishers, likely influenced by awareness-raising efforts and market-based initiatives.

Market-based approaches, including the development of commercial markets for invasive species, have been increasingly recognized as promising tools to reduce their populations while supporting local economies (Pasko and Goldberg 2014). However, experiences from lionfish commercialization in Mexico highlight that such strategies may also create new socio-ecological dilemmas, including dependency on the species for income, inequitable access to benefits, and a shift in focus from eradication to exploitation (Quintana et al. 2022; Azzurro et al. 2024).

Currently, the only fishing gear specifically targeting lionfish in Turkish seas are TTNs with different mesh sizes (mostly 7.2 and 9.0 cm), which are commonly used by SSF primarily targeting common dentex (*Dentex dentex*), red porgy (*Pagrus pagrus*), groupers *(Epinephelus aeneus, E. costae*) and other commercial species. However, the size selectivity of trammel nets in the Mediterranean has been found to be lower compared to gillnets (Lucchetti et al. 2020). Trammel nets are less selective in capturing target fish species and sizes due to their structure, which consists of three layers of netting: two outer layers with large mesh and an inner layer with small mesh that is loosely hung. When a fish pushes through the inner mesh and into one of the outer layers, it forms a pocket, trapping the fish (He et al. 2021). As a result, this design can unintentionally capture a wider range of non-target species and sizes by entangling or trapping them. On the other hand, the morphological body structure of lionfish may contribute to the capture of smaller individuals in these nets.

To date, only a few studies have investigated the interactions between lionfish and fishing gear in the Mediterranean. This study therefore aims to estimate the size selectivity and length-dependent catch efficiency of TTNs made of multifilament polyamide with mesh sizes of 7.2, 9.0, and 10.0 cm for lionfish in the region. The findings are expected to provide valuable insights for the fisheries sector, supporting small-scale fishers in effectively targeting lionfish and enhancing their market presence – thereby creating pressure on this NIS through a dual-benefit.

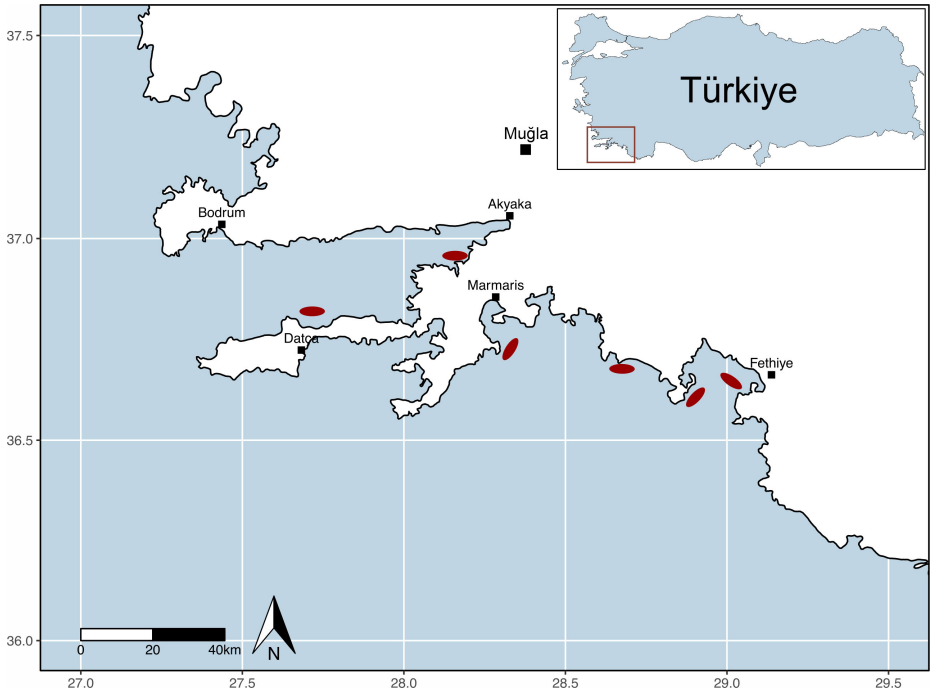


Figure 1. Study area and stations where thick trammel nets samplings were carried out.

Materials and methods

Fishing trials were conducted in commercial fishing grounds in the southern Aegean Sea (eastern Mediterranean) between 30 August 2022 and 13 September 2024 mostly in the summer when lionfish landing was the highest, according to the SSF operating in the area (Figure 1). The areas were selected according to the fishermen's knowledge about the grounds where lionfish are abundant. Lionfish were initially caught in large quantities as bycatch in these areas over the last five years. There are Special Environmental Protection Areas (SEPA) located close to the areas where the trials were carried out in Gökova and Fethiye Bay and Marmaris, and the removal of invasive lionfish from waters adjacent to Marine Protected Areas (MPAs) is crucial for protecting biodiversity.

The trials were conducted using four different small-scale fishing vessels in 6 stations. The boats ranged in size from 8.0 to 10.7 meters in length and had engine power ratings between 20.9 and 100.8 horsepower.

All TTNs used in the experiments consist of three layers and are made from the same material-multifilament polyamide. The inner layer mesh sizes of the TTNs are 7.2 cm, 9.0 cm, and 10.0 cm, while the outer layers consistently have a mesh size of 36.0 cm. As the mesh size increases, the twine thickness also increases proportionally, using thickness of 210 d / 9, 12, and 15. Each net panel, hung at a 50% hanging ratio, measures 100 meters in length. Floats, made of polyethylene, were attached along the headrope with one float followed by four empty spaces. The footrope was weighted with 50 g leads, attached in a pattern of one lead followed by one empty space (Figure 2).

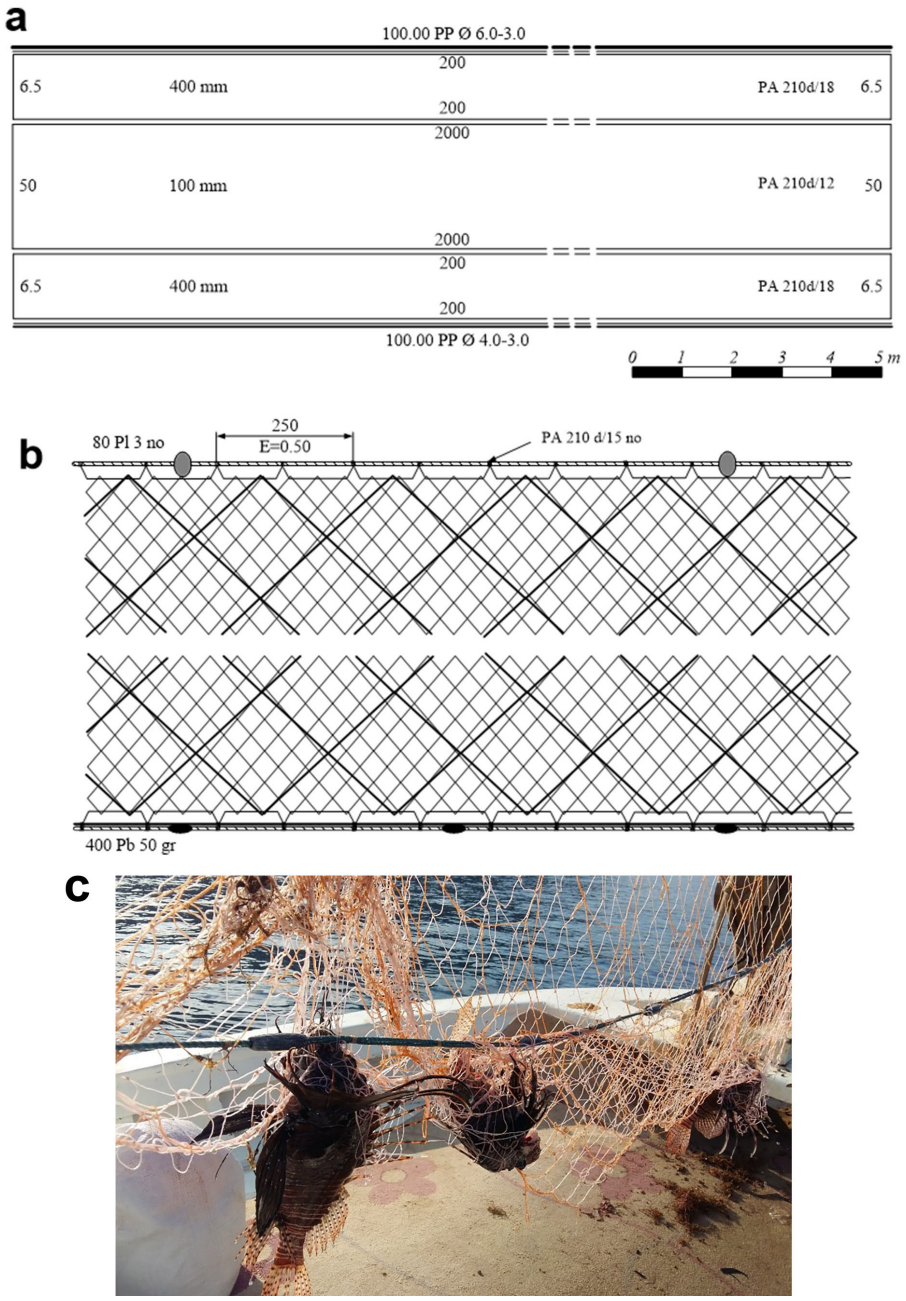


Figure 2. (a) Technical and (b) rigging plans of the thick trammel net for lionfish and (c) the species caught in the net. Photo by Zafer Tosunoğlu.

TTNs were deployed at twilight and retrieved at daybreak, resulting in an average fishing duration of 16.7 hours. Fishing was carried out at depths between 10 to 100 meters. When deployed on or around rocky reef areas, these nets follow a unique pattern, differing greatly from the setup of other gillnets and entangling nets. In practice, these nets are not deployed along depth contours in straight transects, but rather from shallow to deeper zones in a shore-to-sea orientation, particularly around complex rocky reef habitats. Only a few deployments were conducted strictly along defined depth contours. Therefore, depth was not used as a stratification variable in the analysis, as standardization based on depth contours could not be achieved under typical operational conditions.

To assess the effect of mesh size on catch efficiency and size selectivity, standardized net deployments were conducted across six stations mainly on rocky reef areas and presumed differences in lionfish densities. At each station, three different mesh sizes (7.2 cm, 9.0 cm, and 10.0 cm) were used, with various length of net deployed per mesh size. Therefore, the quantities of species caught by all nets were standardized to a reference length of 10,000 m. No prior quantitative assessment of lionfish abundance was conducted at the selected stations. However, consistent sampling effort across all mesh sizes and stations was applied to reduce spatial bias and enable meaningful comparisons of the size distribution and catch efficiency derived from the fish length data.

The total lengths of lionfish caught in each net fleet with different mesh sizes were measured using a board with a precision of 1 mm. Length-frequency distributions were then classified in 1-cm class intervals for selectivity analyses. The total weights of the species caught in each net fleet during each operation were measured using a digital scale with a precision of 1 g.

The normal distribution of the data was assessed using the Shapiro-Wilk test. An ANOVA with the Tukey^{HSD} test was used to compare fish lengths among the different mesh sizes. The ggstatsplot v 0.12.0 (Patil 2021), agricolae v. 1.3-6 (Mendiburu 2023) and ggplot2 v 3.4.3 (Wickham 2016) R packages were used in the evaluation and visualization of the data. The two-way Kolmogorov-Smirnov test was performed to determine differences in the length-frequency distribution of fish captured by different mesh sizes, and the fishmethods (v.1.13-1) R package was used in this process (Nelson 2025). The RStudio program (v.2024.12.1) was utilized for the execution of the R packages referred to (Posit team, 2025).

The SELECT (share each length's class catch total) method was used to estimate the length selectivity of the TTNs (Millar 1992; Millar and Holst 1997; Millar and Fryer 1999), which is an indirect estimation method. According to restrictive alternatives (e.g. Holt 1963), the SELECT method is a statistical model that estimates selectivity curves and offers a consistent approach for conducting selectivity analyses (Balık 2008). SELECT method is described by the equation:

$$n_{lj} \sim Po\left(p_j . \lambda_l . r_j(l)\right)$$

and the log-likelihood of n_{lj} is

$$\sum_l \sum_j \{n_l log_e[p_j . \lambda_l . r_j(l) - (p_j . \lambda_l . r_j(l))]\}$$

where n_{lj}: the number of fish of length l caught in mesh size j; λ_l the abundance of length l fish contacting the gear; p_j: the relative fishing

intensity of the net of mesh size *j*; r_j (*l*): the retention probability of length l fish in the mesh size *j* (Adamidou et al. 2023).

The length selectivity of each mesh size was described by five different functions (normal location, normal scale, lognormal, gamma and bi-normal) of the SELECT method (Millar and Fryer 1999). Data were analysed in RStudio software by using R codes developed by Millar (2015, 2017, 2024). The model parameters were primarily estimated for TTNs with the lowest mesh size (7.2 cm), and the selection curves for all other mesh sizes scale proportionally to a mesh size of 7.2 cm (Park et al. 2011). The most suitable model was chosen based on the lowest deviation value.

Length-dependent catch comparison and catch ratio analyses were conducted to compare the catch efficiency between different mesh sizes of TTNs (Cerbule et al. 2022; Brinkhof et al. 2023; Altuntaş et al. 2024). The length-dependent catch comparison rate CC(l,v) and catch ratio CR(l,v) were estimated for *P. miles* to investigate potential differences in catch efficiency for each mesh size. Within each pair, panels were deployed at the same time of day, depth and station, enabling a paired catch comparison analysis (Lomeli et al. 2020). Equation [1] was used to assess the relative length-dependent CC_l of changing from one mesh size to another (Cerbule et al. 2021; Lomeli et al. 2021; Fakıoğlu et al. 2023).

The modelled CC(l,v) that was calculated by Equation [1] was obtained using maximum likelihood estimation by minimizing Equation [2] (Lomeli et al. 2021; Fakıoğlu et al. 2023). The experimental CC_l was modelled by the function CC(l,v) using Equation [3] (Burnham and Anderson 2002; Herrmann et al. 2017). Subsequently, Equation [4] was used to calculate the direct relative catch efficiency values of the compared TTNs panels of different mesh size (Cerbule et al. 2021; Lomeli et al. 2021; Fakıoğlu et al. 2023).

$$CC_l = \frac{\sum_{j=1}^{h}\left\{\frac{nd_{lj}}{qd_j}\right\}}{\sum_{j=1}^{h}\left\{\frac{nd_{lj}}{qd_j}+\frac{ns_{lj}}{qs_j}\right\}} \quad 1$$

$$-\sum_{j=1}^{h}\sum_{l}\left\{\frac{nd_{lj}}{qd_j}\,x\ln[CC\,(l,v)]+\frac{ns_{lj}}{qs_j}\,x\ln[1.0-CC(l,v)]\right\} \quad 2$$

$$CC\,(l,v) = \frac{\exp\left[f\left(l,v_{0,}\ldots,v_k\right)\right]}{1+\exp\left[f\left(l,v_{0,}\ldots,v_k\right)\right]} \quad 3$$

$$CR(l,v) = \frac{CC\,(l,v)}{[1-CC(l,v)]} \quad 4$$

A double bootstrapping method with 1000 bootstrap repetitions was used to estimate the Efron 95% confidence intervals (CIs) for both the catch comparison and catch ratio (Efron 1982). The catch efficiency equilibrium points of the compared panels were 0.5 for the catch comparison rate and 1.0 for the catch ratio (Fakıoğlu et al. 2023). The statistical software programme SELNET was used to perform the relative catch efficiency analysis in this study (Herrmann et al. 2012, 2016).

Results

Nearly half (56.4%) of the fish caught with TTNs in the Southern Aegean Sea are alien species, many of which are invasive (Lionfish, *Siganus* spp.). Notably, lionfish dominate the catch composition with a biomass of 48.8%, far exceeding the biomass of commercially valuable target species such as grouper species (8.2%), common dentex (3.9%), and red porgy (2.1%) (Supplementary material Table S1). The catch composition under the category "Other species" accounts for 30.8% of the total catch weight. Notably, elasmobranch species, including sharks and rays, constitute approximately 69% of this group. Within the "Other species" weight, sharks represent around 60%. The incidental capture of one individual of *Carcharias taurus* (sand tiger shark) and three individuals of *Mustelus mustelus* (smooth-hound shark) in nets with a 90 mm mesh size significantly contributed to the high proportion of elasmobranchs within the catch composition.

As a result of the fishing trials, 771 *P. miles* were caught, with total lengths ranging from 18.2 to 42.7 cm. The total number and mean total length of lionfish caught are listed for each mesh size in Table S2. The number of lionfish per 1000 m net panel ($CPUE_N$) revealed the following number of individuals for each mesh size: 20 for 7.2 cm, 19 for 9.0 cm and 13 for 10.0 cm. The range and confidence interval (CI) for mean total length were widest at the 7.2 cm mesh size and narrowest at the 9.0 cm mesh size, as shown in Table S2.

Captured lionfish exhibited a relatively wide size range across all mesh sizes; however, the mean total length showed a slight but statistically significant increase with increasing mesh size ($p < 0.05$) (Figure 3, Table S2).

The estimated selectivity parameters of TTNs with a mesh size of 7.2 cm for lionfish are given in Table S3. The estimated optimum catch lengths for TTNs with a 7.2-cm mesh size varied between 24.45 and 26.70 cm for the applied models, like the predicted model lengths. The ratio of deviance correction factor (deviance / degree of freedom (df)) was found to be higher than the one (1) for all models. The bi-normal model was chosen as the most suitable one for the current data set due to its lowest deviance in equal fishing power. p-value of bi-normal model was computed as 0.55 bigger then 0.05.

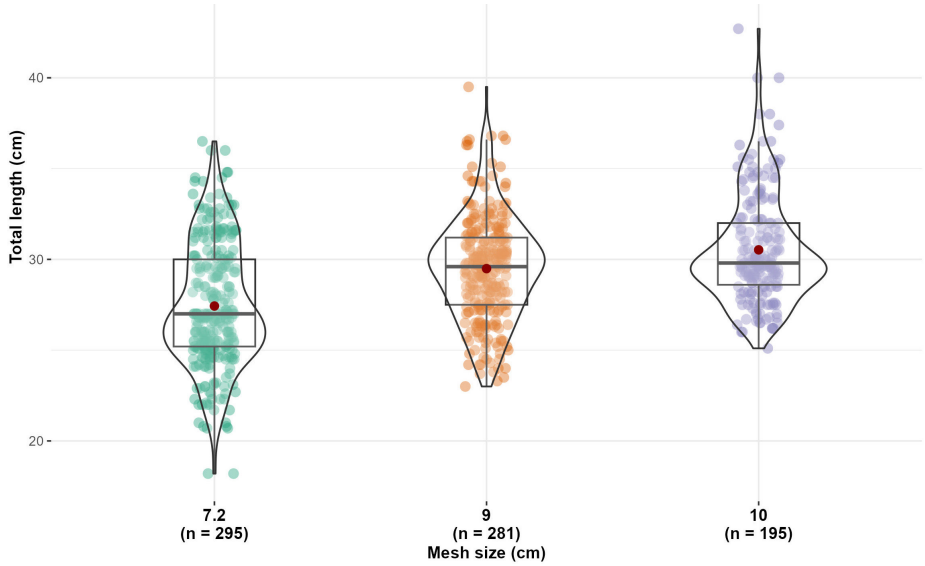


Figure 3. Box plot showing distribution and mean total length (red point) values of caught lionfish by mesh size.

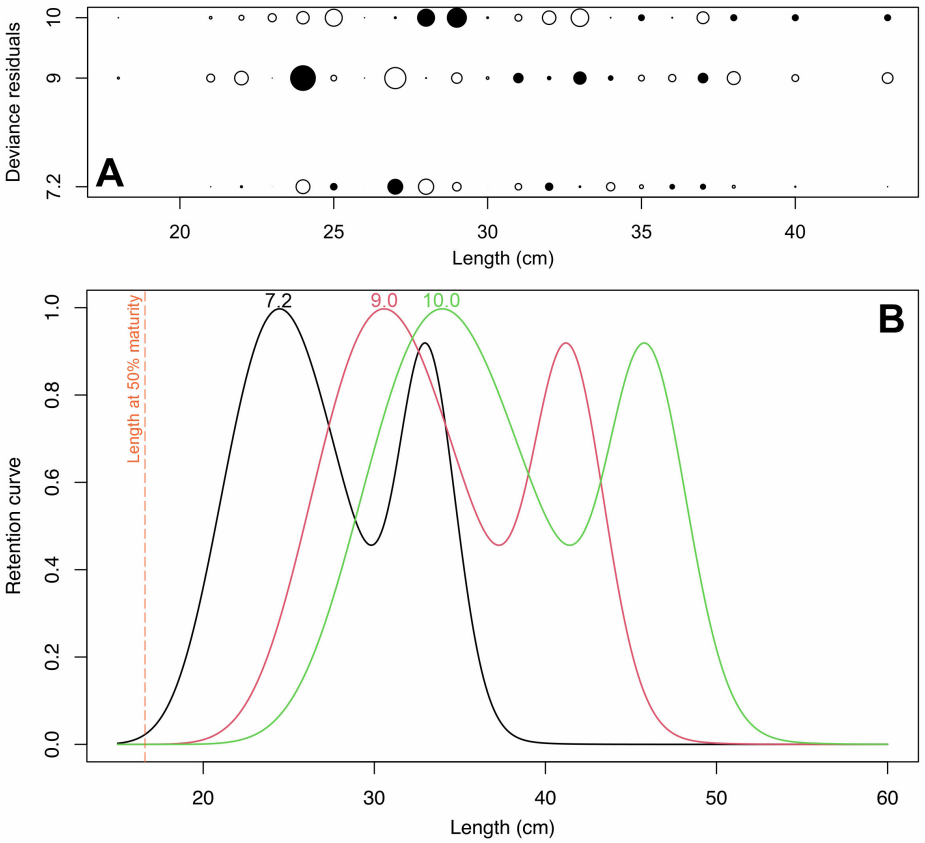


Figure 4. The respective deviance residual plots (A) and selectivity curves (B) of experimental thick trammel nets for *Pterois miles*. Full circles indicate a positive residual and open circles a negative residual. The bubble size is proportional to the residual value.

The selection curves and deviance residuals plot of the experimental TTNs are presented in Figure 4A, B. Due to the relatively equal distribution of positive and negative deviations, the deviance residual plots graph is acceptable for model validation (Figure 4A). Notably, the arms of the selectivity curves become increasingly wider as mesh size increases (Figure 3B).

This observation corresponds to the spread values of mesh sizes given in Table S4.

Estimated model lengths (optimum catching lengths) of TTNs were computed as 24.45, 30.56, and 33.95 cm for TTNs with mesh sizes of 7.2, 9.0 and 10.0 cm, respectively (Table S4). The spread values of the panels showed differences between 3.56 and 4.94 cm.

Kolmogorov-Smirnov (K-S) test results indicated that there were no significant statistical differences in the length frequency distributions of *P. miles* caught by all TTNs, except for the comparison of the mesh sizes of 7.2 and 9.0 cm (Table S5).

Three different TTNs mesh sizes were used in the catch efficiency analysis. A total of six one-by-one comparisons [7.2–9.0], [7.2–10.0], [9.0–10.0]) were conducted to determine the catch efficiency of different mesh sizes. The fitted model's p-value, deviance and df were given in Table S6, for the comparison of TTNs with mesh sizes of 7.2, 9.0 and, 10.0 cm. The experimental data were evaluated as poor for the modelled catch comparison rates because the estimated p-value was below 0.05 for (7.2–10.0) and (9.0–10.0) matches. Length class, in the 18–24 cm statistical differences were found in catch ratios between TTNs with mesh sizes of 7.2 and 9.0 cm (Table S6; Figure 5). There were no statistical differences in other length class and comparisons (Table S6).

Discussion

Due to the significant decline in target species captured by TTNs in the southern Aegean in recent years, lionfish have become a target species for many SSFs using this type of net, although not preferred. Therefore, it can be claimed that these nets are the most important tool to prevent the overgrowth of lionfish population, which do not have any significant natural predators in Turkish Seas. In other words, the invasion pressure of lionfish in these seas may be reduced by introducing this to SSF fishing practices. These findings can help manage the lionfish population, which has become the dominant species caught in TTNs in the southern Aegean, by providing detailed information on their catch rates, fishing areas and size characteristics.

In this study, a total of 771 lionfish were caught and assessed for selectivity analysis. The sample size of fish caught in similar studies with trammel nets and gillnets has shown significant variation, influenced by factors such as location, net specifications, target species, sampling periods, and fishing duration (Karakulak and Erk 2008; Adamidou et al. 2023; Acarlı et al. 2013). With regards to sampling sizes in these similar studies, it is considered to be sufficient for robust selectivity analysis.

Statistically significant variations were found in the mean total lengths of lionfish captured in TTNs with differing mesh sizes. In contrast to other mesh sizes, a few small individuals (18.2 cm) were caught with a mesh size

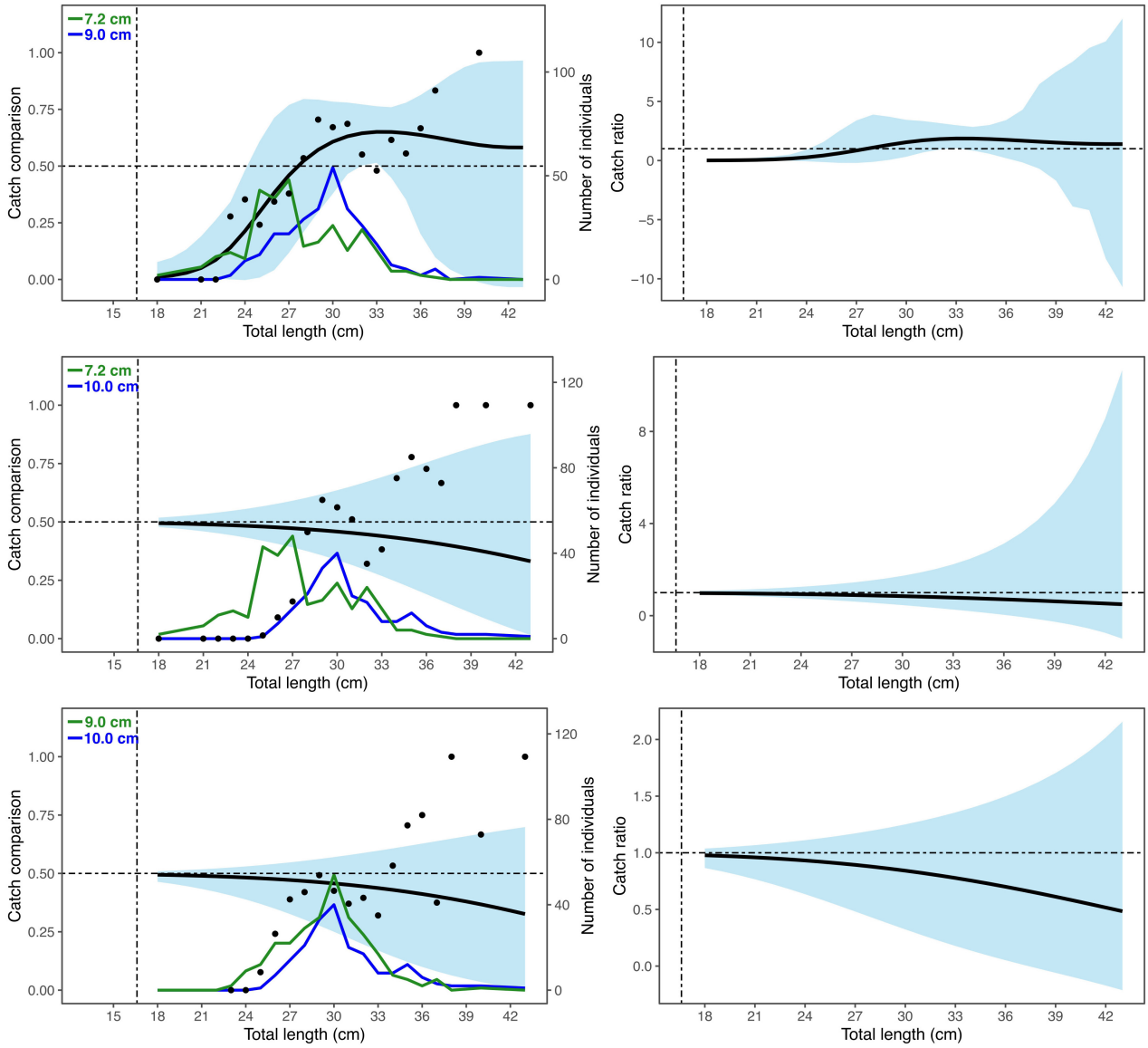


Figure 5. Catch comparison rate and catch ratio for Lionfish. Left: the curve (solid line) represents the modelled catch efficiency fitted to the experimental points (dots). The soft blue band represents 95% CI, and the green (standard) and blue (modified) lines show the length distributions observed in the catch. The dotted horizontal line, located at 0.50, indicates equivalence in catch rates between the compared two mesh sizes. The vertical dashed-dotted line represents the L_{50} length at first maturity. Right: catch ratio curve (solid line) with 95% confidence intervals (soft blue band). The dotted horizontal line, located at 1.0, indicates equivalence in catch rates between the two mesh sizes. The vertical dashed-dotted line represents the L_{50} length at first maturity.

of 7.2 cm (Table S2; Figure 2). This finding indicates that increasing the mesh size of TTNs affects the size distribution of lionfish catches. The primary advantage of using larger mesh sizes, as observed during the operations, is that they facilitate removal of lionfish from the nets, minimizing the risk of injury from their venomous spines. The head or widest part of the lionfish often exceeds the mesh size, making it difficult to extract due to its spines and protrusions. In contrast, lionfish caught in larger-mesh nets can be easily removed by pushing them forward through the mesh opening, which made handling safer and easier, without the fisherman being harmed. Additionally, the thicker netting yarn simplifies the removal process which would encourage SSF to target lionfish.

While lionfish abundance at each fishing location was not directly measured, and the three mesh sizes were not deployed simultaneously and adjacently at each sampling station—which can be acknowledged as a limitation of this study—several lines of evidence suggest that the observed differences in catch characteristics are primarily attributable to mesh size rather than to local population variation. First, fishing effort was standardized across all net panels, therefore selectivity and catch efficiency results were calculated to avoid spatial bias. Second, the statistically significant increase in mean total length and the shift in optimum catch lengths across mesh sizes support the presence of gear selectivity. Third, the catch comparison models, and selectivity curves demonstrate consistent differences in size distributions across mesh types. While some influence of local availability cannot be entirely ruled out, the consistent trends across mesh sizes, including significant differences in catch ratios for specific length classes (Table S6; Figure 4), indicate that mesh size had a primary and measurable effect on catch composition.

The SELECT method, widely used for estimating selectivity in gillnets and entangling nets, was applied to assess the selectivity of TTNs for lionfish. This method, increasingly favoured in recent research (Aydın et al. 2018; Tesfaye 2019; Xu et al. 2021; Dereli et al. 2022; Adamidou et al. 2023; Demirol and Cilbiz 2023) is a statistical model that provides comparative catch selection curves and offers a cohesive approach to selectivity analyses (Balık 2008). A key reason for choosing the SELECT method was the challenge of establishing a standard fishing design during sampling. By using a flexible fishing approach that aligns with SSF's regular practices, the study aimed to encourage SSF to adapt their behaviour, enabling them to target lionfish with familiar gear.

The bi-normal model was found to be most suitable for collecting catching data regarding unimodels (normal scale, normal location, gamma, log-normal). Unimodels are ideal for narrow length catch ranges and bell-shaped selectivity curves (Akamca et al. 2010). However, as in this study, the bi-normal model is more appropriate when fish are caught by meshes involving wedging, entangling and pocketing and there is a wide length range in the captured fish (Holt 1963; Hovgård 1996; Akamca et al. 2010). The use of the bi-normal model for lionfish, which have an abnormal body structure and extraordinary fins, is reasonable in this context. In fact, the bi-normal model has been identified as the most suitable one in numerous trammel net selectivity studies (Erzini et al. 2006; Akamca et al. 2010; Kalaycı and Yeşilçiçek 2012; Aydın et al. 2016, 2018; Cilbiz et al. 2017; Adamidou et al. 2023).

The estimated deviance correction factor (deviance/df) indicated over-dispersion (Table S3). Over-dispersion suggests either a lack of fit or a violation of the assumption of an underlying Poisson distribution (Holst et al. 1998; Tesfaye 2019). In the study, the correction factor was calculated as

1.9, which is slightly higher than the desired value of 1. Considering that trammel nets, due to their structure, have lower size selectivity than gillnets and capture species with unusual body structures, the predicted correction factor for the bi-normal model is considered quite acceptable. It can also be seen from the deviance residual plot (Figure 3A) graph that the deviations are well controlled. On the other hand, higher correction factor is not unusual, as over-dispersion has been reported in most set net selectivity studies (Erzini et al. 2006; Ayaz et al. 2010; Acarlı et al. 2013; Tesfaye 2019; Dereli et al. 2022; Adamidou et al. 2023).

Previous studies have estimated the size at sexual maturity for lionfish (*Pterois* spp.) to be around 18–19 cm in total length (Gardner et al. 2015). Region-specific data from the southern Aegean Sea further suggest that first reproductive lengths begin at approximately 16.6 cm for females and 16.8 cm for males (Ulaş et al. *unpublished data* 2023). These benchmarks are relevant to the present study, as they indicate that all lionfish individuals captured in our experimental TTNs—regardless of mesh size—were above the estimated size at first maturity. This suggests that the current trammel net configurations, even with the smallest tested mesh size (7.2 cm), do not result in the capture of immature individuals. While this may be considered advantageous from a marketability standpoint, it presents a potential drawback for population control efforts, as younger individuals remain largely unaffected by the gear.

It is noteworthy that the morphological characteristics of lionfish, particularly its deep body and prominent spines, may result in individuals of varying sizes becoming entangled across different mesh sizes, irrespective of mesh selectivity criteria. This structural susceptibility likely contributes to an overlap in the size distribution of catches among mesh size categories, potentially complicating efforts to achieve size-specific selectivity (Figure 3).

Although lionfish were caught across a broad depth range (10–100 m), the deployment method of the nets—typically extending from shallow to deeper zones—did not allow for stratified analysis by specific depth intervals. As a result, potential depth-related patterns in lionfish abundance or size distribution could not be assessed in this study. Given that depth can influence both the behaviour and distribution of lionfish, future research incorporating depth-stratified sampling or remote visual census methods could provide valuable insights into habitat-specific catch dynamics and improve selectivity-based management strategies. Ongoing acoustic telemetry research such as the one in Gökova Bay (Z. Kızılkaya *pers. comm.* 2025) may help align gear use with habitat-specific lionfish behaviour (Özgül 2022).

This study focused on assessing the size selectivity and catch efficiency of trammel nets targeting the invasive lionfish, based on standardized length-based data across multiple mesh sizes. To improve the broader applicability of the findings, sampling was intentionally conducted at stations representing a range of depths and benthic structures. However,

variables such as habitat complexity, station identity, and depth were not incorporated into the selectivity models due to methodological constraints. The statistical approaches used in this study are designed to analyse length-frequency data in relation to mesh size and are not structured to accommodate such categorical or spatial variables. Addressing these factors would require a different modelling framework—such as generalized linear mixed models—and a tailored sampling design. Nevertheless, we acknowledge that these environmental variables likely influence catch dynamics, and their inclusion would strengthen future efforts to optimize gear selectivity in complex habitats.

The current study determined the selectivity properties of TTNs commonly used by fishers in the region, previously in economically important native species that have naturally converted to the lionfish fishery. These findings will benefit fisheries management authorities in deciding the fate of the species in the region using a fish stock approach and their adaptive management. If an all-out struggle is to be undertaken, the species must be fished at lengths below the L_{50} maturity size, in which case there is a need to lower the mesh size used by fishermen. A bycatch of juvenile individuals would result from this, which would negatively affect other native species.

Given the irreversible introduction of lionfish in the Mediterranean and the compounding effects of climate change and biodiversity loss, a rigid or one-time management solution is unlikely to be effective. Instead, an adaptive management approach—one that allows for flexible, responsive strategies based on regular monitoring (e.g, adjusting mesh size based on periodic catch monitoring), stakeholder feedback, and new ecological knowledge—may offer the most realistic pathway forward (Levin and Möllmann 2015). This is particularly relevant in Mediterranean fisheries, where ecosystems are under simultaneous pressure from warming seas, overfishing, and biological invasions (Katsanevakis et al. 2014). Aligning with the UNEP/MAP (2017) recommendations for invasive species, promoting adaptive management could support not only lionfish population control but also socioeconomic resilience among SSF.

Conclusions

This study provides the first quantitative assessment of the size selectivity and catch efficiency of TTNs with mesh sizes of 7.2, 9.0, and 10.0 cm for lionfish in the Mediterranean Sea. The findings show that increasing mesh size results in a statistically significant shift in the mean total length and optimum catch size of lionfish, with no individuals below size at first maturity captured in any net. The bi-normal model best represented the selectivity pattern, consistent with the species' wide size range and distinctive morphology.

TTNs, already commonly used by SSF in the region, offer a practical and scalable method for selectively targeting lionfish. Compared to spearfishing—which remains limited to accessible shallow waters and requires intensive manual effort—TTNs enable lionfish removal over wider areas and deeper depths, with reduced physical risk to fishers due to easier handling of individuals in larger and thicker meshes. While spearfishing may be more precise and effective for targeting small aggregations, TTNs have the advantage of integration into existing fishing operations, potentially offering a cost-effective tool for lionfish control in SSF. TTNs require minimal new investment for SSF already using these nets, whereas spearfishing demands costly dive gear and training.

Overall, the study supports the use of selective fishing gear as part of an adaptive management approach for controlling invasive lionfish populations. Promoting mesh size modifications in TTNs may help balance ecological goals with fisher safety, while contributing to broader efforts to integrate lionfish into local fisheries management and markets.

Authors' contribution

Tosunoğlu: conceptualization, methodology, writing – reviewing and editing. Ulas: data curation, writing – original draft preparation. Cilbiz: formal analysis, visualization, conceptualization, writing – review editing. Kok: writing – reviewing and editing, funding acquisition, project administration.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Standardised catch weight and percentages of species caught by TTNs based on mesh size.
Table S2. Total length distribution, catch number and length comparison results of Lionfish by experimental thick trammel nets.
Table S3. Selectivity parameters estimate based on the use of four uni-model and one bi-model.
Table S4. Model length and spread values by mesh size for the best-fit model (bi-normal) for *Pterois miles*.
Table S5. Results of the K–S test used to compare length frequency distributions between pairs of thick trammel nets with different mesh sizes.
Table S6. Catch ratio (CR) results (in %) at different lengths and fit statistics for the catch comparison analysis for three mesh size comparison.

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