

## Mediterranean Marine Science

Vol 20, No 3 (2019)



**Mesh sticking probability in fishing gear selectivity: Methodology and case study on Norway lobster (*Nephrops norvegicus*) and mantis shrimp (*Squilla mantis*) in the Mediterranean Sea creel fishery**

JURE BRČIĆ, BENT HERRMANN, MARINA MAŠANOVIĆ, SVJETLANA KRSTULOVIĆ ŠIFNER, MATEJA BARANOVIĆ, FRANE ŠKELJO

doi: [10.12681/mms.19018](https://doi.org/10.12681/mms.19018)

### To cite this article:

BRČIĆ, J., HERRMANN, B., MAŠANOVIĆ, M., ŠIFNER, S. K., BARANOVIĆ, M., & ŠKELJO, F. (2019). Mesh sticking probability in fishing gear selectivity: Methodology and case study on Norway lobster (*Nephrops norvegicus*) and mantis shrimp (*Squilla mantis*) in the Mediterranean Sea creel fishery. *Mediterranean Marine Science*, 20(3), 487–495. <https://doi.org/10.12681/mms.19018>

## Mesh sticking probability in fishing gear selectivity: Methodology and case study on Norway lobster (*Nephrops norvegicus*) and mantis shrimp (*Squilla mantis*) in the Mediterranean Sea creel fishery

Jure BRČIĆ<sup>1</sup>, Bent HERRMANN<sup>2,3</sup>, Marina MAŠANOVIĆ<sup>4</sup>, Svjetlana KRSTULOVIĆ ŠIFNER<sup>1</sup>,  
Mateja BARANOVIĆ<sup>4</sup> and Frane ŠKELJO<sup>1</sup>

<sup>1</sup> University of Split, University Department of Marine Studies, Ruđera Boškovića 37, 21000 Split, Croatia

<sup>2</sup> SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850 Hirtshals, Denmark

<sup>3</sup> University of Tromsø, Breivika, N-9037 Tromsø, Norway

<sup>4</sup> Underwater research club of University of Split, Livanjska 5, 21000 Split, Croatia

Corresponding author: [jure.brcic@unist.hr](mailto:jure.brcic@unist.hr)

Handling Editor: Stelios SOMARAKIS

Received: 8 November 2018; Accepted: 2 April 2019; Published on line: 27 August 2019

### Abstract

Fish or crustaceans stuck in the fishing gear meshes can lead to operational problems in some fisheries and thereby affect the economic gain. However, mesh sticking probability has never been formally quantified as a part of the estimation of fishing gear size selectivity. Therefore, this study developed a size selection model and estimation procedure that, besides the size dependent retention and escape probabilities, includes the size dependent mesh sticking probability. The new method was applied to quantify the size dependent retention, sticking and escape probabilities for mantis shrimp (*Squilla mantis*) and Norway lobster (*Nephrops norvegicus*) in creels with 41 mm square mesh netting. The mesh sticking probability was found to display a bell-shaped curvature with a maximum value for a specific carapace length and decreasing probabilities for both smaller and bigger individuals. For mantis shrimp the maximum sticking probability was found for 32.5 mm carapace length with a value at 13.5%, while 63.1% and 23.4% of that size were respectively retained inside the creels and escaped. For Norway lobster the maximum sticking probability was 2% and occurred for 34.0 mm carapace length. The method and estimation procedure presented in this study might be applicable for quantifying mesh sticking probability as an integral part of future fishing gear size selectivity studies on other species and fisheries.

**Keywords:** Sticking probability; selectivity; Norway lobster; mantis shrimp; creels.

### Introduction

Majority of fishing gears are made of netting. Active gears, such as trawls, use netting to guide fish toward the codend, where they are collected and held during the tow. Passive gears, such as gillnets, use the netting to trap fish by meshing/enmeshment (gilling, wedging, snagging and entangling) as they try to pass through the netting (Hovgård & Lassen, 2000). However, meshing can also occur in towed gear (ICES, 2012; Pol *et al.*, 2016), where those fish are often referred to as “stickers”. Sticker aggregations in certain parts of a trawl can indicate areas where fish are attempting to escape, and can often be used for stipulating optimal position for bycatch reduction devices, such as square mesh panels (Arkley, 2001). The presence of stickers in the trawl gears often presents a problem for fishermen as they have to remove them and clean the net prior to the subsequent shooting (ICES,

2012). These stickers are often damaged and unsalable (Pol *et al.*, 2016). This may be challenging, especially in pelagic trawl fisheries where the volume of catch is often very high. Sometimes changes in mesh size can partially solve this problem. For example, reduced growth rate of herring in the Baltic region in 1990s incited trawl fishermen to use smaller meshes in order to avoid stickers (Rahikainen *et al.*, 2004). On the other hand, increase in mesh size in the west of Scotland resulted in a higher number of stickers, thus increasing the overall number of discarded fish (Anonymous, 2011). In addition, if stickers are not removed prior to the subsequent shooting of the gear, they attract seabirds which can get entangled in the netting during the shooting as they dive into the trawl for feeding on stickers (Løkkeborg, 2011). This is especially pronounced in trawl fisheries targeting small fish (Weimerskirch *et al.*, 2000). Some researchers speculate that removal of stickers could also help reducing seal by-

catch in trawl nets by making net less attractive to seals (Hamer & Goldsworthy, 2006).

The literature on mesh sticking in trawl fishery is scarce, and a formal methodology for quantifying it as an integral part of the size selection modelling, has not been developed yet. Even less literature is available on other gear types, with the exception of gillnets. For example, sticking in the Mediterranean Norway lobster (*Nephrops norvegicus*) creel fishery has never been reported. This fishery is not as large in catch volume as the bottom trawl fishery, but it is an important small-scale fishing activity that targets a highly priced species (Eriksson, 2006; Ridgway *et al.*, 2006). In Croatia, this fishery is a year-round activity practiced almost exclusively in the internal waters. The creels with square mesh netting of either 36 mm or 40 mm (Anonymous, 2015) are deployed from the small artisanal vessels in a longline system (Soldo *et al.*, 1999). In our study, stickers were recorded for the first time in this fishery and were used to address the following objectives:

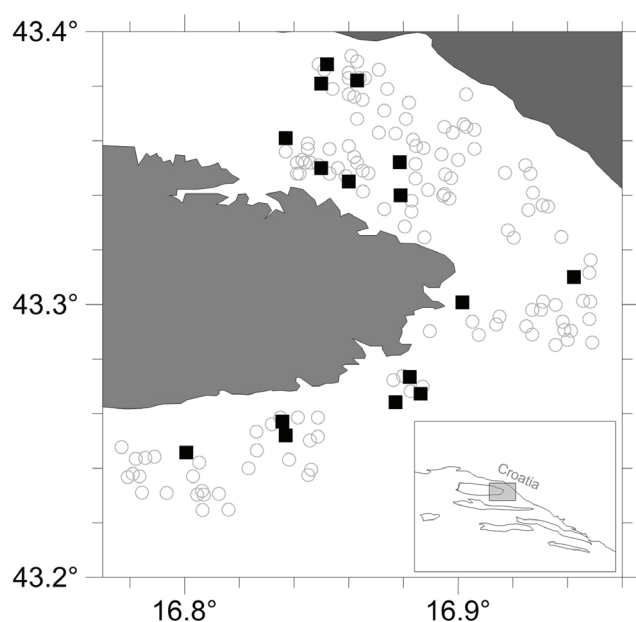
Developing a new method for quantifying sticking probability in creel fishery as an integral part of size-selectivity estimation.

Applying the new method to quantify mesh sticking probability for two main crustacean species in the Mediterranean Norway lobster creel fishery.

## Materials and Methods

### Experimental fishing trials

Experimental fishing trials were conducted in the Adriatic Sea from May 26<sup>th</sup> to July 5<sup>th</sup> 2016 (Fig. 1). A small commercial fishing vessel (6.9 m, 84 hp) was used to deploy test creels made of 41 mm ( $\pm 0.72$  mm SD) polyamide netting mounted to obtain a square mesh



**Fig 1:** Map of the sampling area showing position of test (empty circles) and control (solid squares) longline deployments.

shape, and control creels of the same dimensions (700 mm x 450 mm x 265 mm), but with 12 mm polyamide netting meshes. Both creels had two entrances placed opposite to each other. The creels were used in a longline system, each with 30 creels, deployed early in the morning and retrieved after 24h soaking if the weather permitted, following common commercial fishing practice in the fishery. Before deployment all creels were baited with pieces of fresh Atlantic horse mackerel ( $43.29 \text{ g} \pm 11.33 \text{ g SD}$ ) without using any bait protection.

After retrieving the creels, a total catch of each longline was categorized in one of the three groups: catch group caught inside the test creel, stuck in the test creel meshes or caught in the control creels. Each catch group was sorted and lengths measured. Carapace length of mantis shrimp (*Squilla mantis*) and Norway lobster (*Nephrops norvegicus*) were measured to the nearest 1 mm.

### Model for size selection

There are three possible scenarios for a crustacean entering the creel: i) retaining inside the creel ( $r(l)$ ), ii) sticking in the creel mesh ( $s(l)$ ), iii) escaping through the creel mesh ( $e(l)$ ).

$l$  denotes carapace length and its presence in  $r(l)$ ,  $s(l)$  and  $e(l)$  signals that we anticipate that these probabilities will depend on the size of the crustacean that entered the creel. To model these probabilities, we used a sequential model with two barriers dividing into three chambers with each chamber associated exclusively to one of the three options considered (Fig. 2).

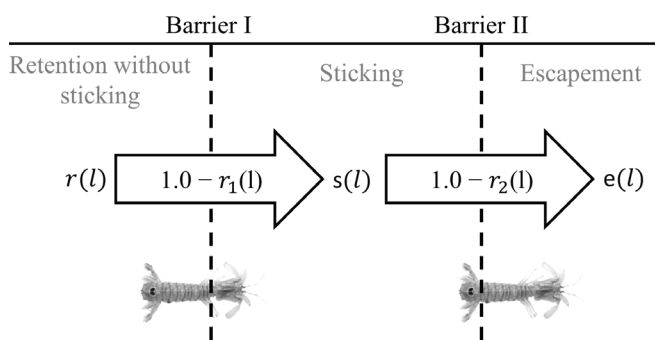
In order to escape, crustacean starting inside the creel needs to pass barrier I and barrier II (Fig. 2). An individual that does not pass barrier I will remain retained inside the creel, while an individual that passes barrier I, but fails to pass barrier II, will be stuck in a mesh (Fig. 2).

Barrier I can be interpreted as the barrier that prevents full or partway passage through the mesh. In case a crustacean passes barrier I, barrier II represents the condition that can prevent it from passing completely through the mesh in order to escape (Fig. 2). The above considerations lead to the following model for the length dependent probability for each of the three scenarios:

$$\begin{aligned} r(l) &= r_1(l) \\ s(l) &= (1.0 - r_1(l)) \times r_2(l) \\ e(l) &= (1.0 - r_1(l)) \times (1.0 - r_2(l)) \end{aligned} \quad (1)$$

If  $r_2(l)$  is zero, then the sticking probability is also zero because barrier II does not exist, implying that all individuals that have passed the first barrier will escape.  $r_1(l)$  can, in case of zero sticking, be interpreted as the traditional creel size selectivity process. Both  $r_1(l)$  and  $r_2(l)$  are modelled by the traditional s-shaped logit size selection model (Wileman *et al.*, 1996) with respective parameters ( $L50_p$ ,  $SR_p$ ) and ( $L50_s$ ,  $SR_s$ ):

$$r_{\text{logit}}(l, L50, SR) = \frac{\exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)}{1 + \exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)} \quad (2)$$



**Fig. 2:** Schematic representation of the three-chambers sequential model with two barriers used to describe the selection process in the test creels. In order to escape, crustacean starting inside the creel needs to pass Barrier I ( $1 - r_1(l)$ ) and Barrier II ( $1 - r_2(l)$ ). An individual that does not pass Barrier I will remain retained inside the creel, while an individual that passes Barrier I ( $1 - r_1(l)$ ), but is retained by the Barrier II ( $r_2(l)$ ) will be stuck in a creel mesh;  $r(l)$ ,  $s(l)$  and  $e(l)$  represent probabilities of being retained inside the creel, probability of being stuck in a creel mesh and probability of escapement through a creel mesh, respectively.

$L50$  denotes the carapace length for crustaceans that have 50% probability to pass the barrier ( $L50_1$  for barrier I and  $L50_2$  for barrier II in Fig. 2).  $SR$  denotes the difference in carapace length between crustaceans with 75% and 25% probability, respectively, for passing the barrier ( $SR_1$  for barrier I and  $SR_2$  for barrier II in Fig. 2). With model (1), using (2), four parameters have to be estimated to be able to describe the size selection in the creel:  $L50_1$ ,  $SR_1$ ,  $L50_2$ , and  $SR_2$ . As different species have different morphology and behaviour, the values for the parameters will be species specific. Therefore, the analysis was applied separately for specific species.

### Data analysis and parameter estimation

Due to low catches, each longline comprising of 30 creels, was considered as a base unit in the analysis. Catch data were collected in two groups: test and control longlines. The control longlines that retained all sizes were used to sample information on the size composition of crustaceans that could be expected to enter the size selective test creels. In this way the catches from the group of control longlines can be compared with the catches from the test longlines and used in an un-paired estimation method following Sistiaga *et al.* (2016) and as applied by Brčić *et al.* (2018a) in creel fishery. However, compared to the standard un-paired estimation method, the catches from our test longlines were treated in a different manner. This is because they were separated into two-compartment data: individuals retained inside the test creels and those stuck in the test creel meshes.

To estimate the average size selection of the test creels, we compared the pools of catch data from the test creels with the pool of catch data from the control creels. Based on this approach, the experimental data were treated as three-compartment data in the analysis. The first com-

partment comprised individuals retained inside the test creel (RT), the second one comprised individuals stuck in the test creel meshes (ST) and the third one comprised individuals retained by the control creels (RC). The probability that a crustacean would enter one of the creels of the test longlines and one of the creels of the control longline was modelled by the split factor,  $SP$ , as traditionally done for unpaired-gear data analysis (Sistiaga *et al.*, 2016). This means that the probability that a crustacean will enter the test creel is  $SP$ , whereas the probability of entering the control creel is  $1.0 - SP$ , conditioned it enters one of them. All crustaceans caught with the control longlines are retained because of the small mesh size. For a crustacean entering one of the creels included in the analysis (test or control), the probability that it will be retained in one of the creels of the test longline would, based on equation (1), be:

$$SP \times r_1(l, L50_1, SR_1)$$

For a crustacean entering a creel in one of the sets included in the analysis, the probability that it will be stuck in a test creel mesh would, based on equation (1), be:

$$SP \times (1.0 - r_1(l, L50_1, SR_1)) \times r_2(l, L50_2, SR_2)$$

Considering this, the probability  $\gamma$  that a crustacean entering one of the test or control longlines will be observed in one of the three compartments (RT, ST, or RC) can be expressed as:

$$\gamma(l, 50_1, SR_1, L50_2, SR_2, SP) = SP \times r_1(l, L50_1, SR_1) + SP \times (1.0 - r_1(l, L50_1, SR_1)) \times r_2(l, L50_2, SR_2) + 1.0 - SP \quad (3)$$

Based on equation (3) and the considerations above, the probabilities  $p_{RT}$ ,  $p_{ST}$ , and  $p_{RC}$  that a fish or crustacean observed in the catch will be found in the compartment RT, ST, or RC, respectively, can be expressed by:

$$p_{RT}(l, 50_1, SR_1, L50_2, SR_2, SP) = \frac{SP \times r_1(l, L50_1, SR_1)}{\gamma(l, 50_1, SR_1, L50_2, SR_2, SP)} \quad (4)$$

$$p_{ST}(l, 50_1, SR_1, L50_2, SR_2, SP) = \frac{SP \times (1.0 - r_1(l, L50_1, SR_1)) \times r_2(l, L50_2, SR_2)}{\gamma(l, 50_1, SR_1, L50_2, SR_2, SP)}$$

$$p_{RC}(l, 50_1, SR_1, L50_2, SR_2, SP) = \frac{1.0 - SP}{\gamma(l, 50_1, SR_1, L50_2, SR_2, SP)}$$

By using equation (4), the values for the parameters in the selection model (1) can be estimated from the collected experimental data by minimizing the following function with respect to  $L50_1$ ,  $SR_1$ ,  $L50_2$ ,  $SR_2$ , and  $SP$ :

$$-\sum_i \{ \sum_{i=1}^a [nRT_{li} \times \ln(p_{RT}(l, 50_1, SR_1, L50_2, SR_2, SP))] + \sum_{i=1}^a [nST_{li} \times \ln(p_{ST}(l, 50_1, SR_1, L50_2, SR_2, SP))] + \sum_{j=1}^b [nRC_{lj} \times \ln(p_{RC}(l, 50_1, SR_1, L50_2, SR_2, SP))] \} \quad (5)$$

where the outer summation is over length classes  $l$  in the experimental data and the inner summation is over deployments  $i$  (from 1 to  $a$ ) and  $j$  (from 1 to  $b$ ) with, respectively, the test and control setup.  $nRT_{li}$ ,  $nST_{li}$  and  $nRC_{lj}$  are the number of crustaceans caught and length



measured for length class  $l$  in set  $i$  and  $j$  in the respective compartment. Minimizing (5) with respect to the parameters in it, corresponds to maximizing the likelihood for the observed experimental data based on a multinomial model, assuming that the formulated model (4) describes the experimental data sufficiently well. The observed experimental length dependent portioning of the catches between the three compartments RT, ST and RC, which model (4) is expected to describe, are given by:

$$\begin{aligned}\widehat{p_{RT_l}} &= \frac{n_{RT_l}}{n_{RT_l} + n_{ST_l} + n_{RC_l}} \\ \widehat{p_{ST_l}} &= \frac{n_{ST_l}}{n_{RT_l} + n_{ST_l} + n_{RC_l}} \\ \widehat{p_{RC_l}} &= \frac{n_{RC_l}}{n_{RT_l} + n_{ST_l} + n_{RC_l}}\end{aligned}\quad (6)$$

Due to the experimental procedure followed, there was no obvious way to pair the data from the individual test and control deployments. Hence, to estimate the mean selectivity parameters for the experimental gear, the length dependent expected total catches for the test sets were combined and compared with the combined expected total catches for the control deployments as formulated in function (5). The confidence limits for the parameters and curves for the size selection model were estimated using a double bootstrapping method that accounts for the uncertainty resulting from this unpaired nature of the data collection. For this, we adopted and further generalized the method for estimating uncertainty in size selectivity based on unpaired catch data described by Sistiaga *et al.* (2016). This procedure accounts for uncertainty caused by between-deployment variation in size selection processes (Fryer, 1991) and by the un-paired data collection method with groups of test and control sets by selecting independently  $a$  deployments, with replacement from the set of test deployments, and  $b$  deployments from the set of control deployments during each bootstrap iteration. Uncertainty caused by finite sample sizes on deployment level (within-deployment variability) is accounted for by randomly selecting crustaceans with replacement from each of the selected sets for each compartment separately, where the number selected from each compartment in each deployment is the same as the number sampled in that compartment in that deployment. These data are then combined as described above, and the selectivity parameters are estimated again. A total of 1000 bootstrap repetitions were performed to estimate the 95% percentile confidence limits (Efron, 1982; Chernick, 2007) for the selection parameters and curves.

The model's ability to describe the experimental data sufficiently well, was evaluated based on the p-value, model deviance versus degrees of freedom (DOF) and inspection of how the model curve reflects the length-based trend in the data (Wileman *et al.*, 1996). The p-value expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. In case of the poor fit statistics (p-value being  $<0.05$ ; deviance being  $>>DOF$ ), the model curve plots were inspected to determine whether the poor result was due to structural problems when describing the experimental data using the model, or if it was due to

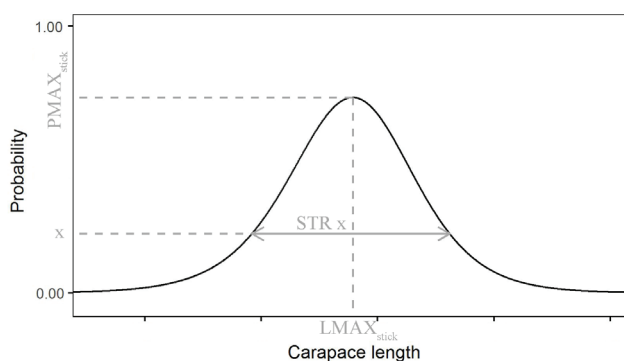
over-dispersion in the data (Wileman *et al.*, 1996).

In addition, the following parameters related to the mesh sticking probability were calculated based on the estimated sticking probability curve using a numerical technique (Fig. 3):  $LMAX_{stick}$  (carapace length where maximum sticking probability occur),  $PMAX_{stick}$  (maximum sticking probability) and  $STR_x$  (size range where the sticking probability is at least  $x\%$ ).  $STR_x$  was estimated in step of 1% up to  $PMAX_{stick}$ .

The analyses described above were all carried out using the software SELNET (Herrmann *et al.*, 2012), which implements the models and the bootstrap method described above.

## Results

A total of 131 tests and 16 control longlines were used during the study. Mantis shrimps were always stuck in the test creel meshes with their carapace protruding outside the creel, while Norway lobsters were always stuck with their tails protruding outside the creel meshes (Fig. 4).



**Fig 3:** Plot of sticking probability curve indicating sticking parameters: sticking range ( $STR_x$ ), maximum sticking probability ( $PMAX_{stick}$ ) and carapace length with maximum sticking probability ( $LMAX_{stick}$ ).



**Fig. 4:** Mantis shrimp (left) and Norway lobster (right) stuck in the test creel meshes.

## Mantis shrimp

Out of a total number of 791 mantis shrimps caught and measured during the study, 581 were retained inside the test creels without sticking, 68 were stuck in the test creel meshes and 142 individuals were retained by the control creels. Number of individuals retained by the test and control creels each fishing day are shown in the Tables 1 and 2, respectively.

**Table 1.** Number of mantis shrimp individuals retained inside the test creel longlines (RT) and stuck in the meshes of test creel longlines (ST) on each fishing day; Test deployment index [*i*]: test deployment indexes used in the inner summation of expression (5) (see Sistiaga *et al.* (2016) for details).

Date	Number of longlines	Deployment index [ <i>i</i> ]	RT	ST
26/05/2016	8	1 - 8	33	5
27/05/2016	8	9 - 16	23	5
28/05/2016	10	17 - 26	37	6
03/06/2016	8	27 - 34	25	2
04/06/2016	9	35 - 43	42	7
05/06/2016	8	44 - 51	24	5
07/06/2016	8	52 - 59	34	5
08/06/2016	8	60 - 67	39	1
14/06/2016	7	68 - 74	50	1
20/06/2016	6	75 - 80	38	3
22/06/2016	6	81 - 86	23	3
26/06/2016	7	87 - 93	39	11
29/06/2016	8	94 - 101	49	1
01/07/2016	9	102 - 110	44	4
03/07/2016	9	111 - 119	47	4
05/07/2016	10	120 - 129	34	5

**Table 2.** Number of mantis shrimp individuals retained by the control creel longlines (RC) on each fishing day; Control deployment index [*j*]: control deployment indexes used in the inner summation of expression (5) (see Sistiaga *et al.* (2016) for details).

Date	Number of longlines	Deployment index [ <i>j</i> ]	RC
26/05/2016	1	1	13
27/05/2016	1	2	6
28/05/2016	1	3	12
03/06/2016	1	4	6
04/06/2016	1	5	8
05/06/2016	1	6	4
07/06/2016	1	7	4
08/06/2016	1	8	17
14/06/2016	1	9	15
20/06/2016	1	10	5
22/06/2016	1	11	12
26/06/2016	1	12	10
29/06/2016	1	13	5
01/07/2016	1	14	11
03/07/2016	1	15	7
05/07/2016	1	16	7

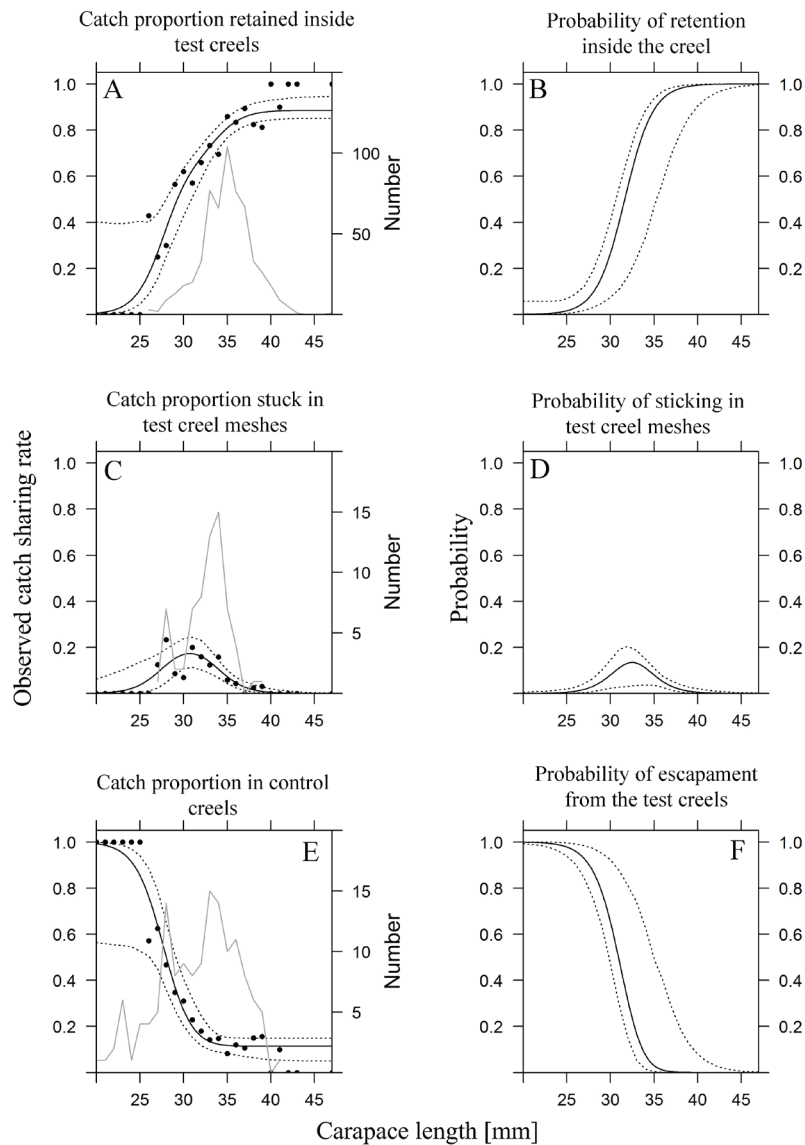
From the Figure 5 it can be seen that the modelled curves reflect well the length-based trend in the experimental data. Fit statistics (Table 3) confirm the visual inspection. The average SP value was not significantly different from the expected value of 0.89 [number of test longline fished (129) divided by total number of longline fished (145)]. The probability of sticking in the test creel meshes exhibited a bell-shaped signature with an average maximum sticking probability of 13.47% estimated for mantis shrimp carapace length at 32.5 mm (Table 3). For carapace lengths less than ~26 mm and over ~39 mm, the sticking probability was estimated to be less than 1% (Fig. 6). The length for maximum sticking probability was not significantly different from the creel L50 value estimated by Brčić *et al.* (2018a) (Fig. 6).

**Table 3.** Modelling results for mantis shrimp;  $L50_1$  is the carapace length for mantis shrimp that has 50% probability to pass the barrier ( $L50_1$  for barrier I and  $L50_2$  for barrier II in Fig. 2);  $SR$  denotes the difference in carapace length between mantis shrimp with a 75% and 25% probability, respectively, passing the barrier ( $SR_1$  for barrier I and  $SR_2$  for barrier II in Fig. 2);  $SP$  is the probability that a mantis shrimp will enter one of the test creels, on condition that it enters one of the creels (test or control);  $STR_x$ : the width of the size range where the sticking probability is at least x%;  $PMAX_{stick}$ : maximum sticking probability;  $LMAX_{stick}$ : carapace length at the maximum sticking probability; DOF: degrees of freedom.

$L50_1$ [mm]	31.63 (30.64 – 35.31)
$SR_1$ [mm]	3.55 (2.63 – 4.95)
$L50_2$ [mm]	33.40 (31.66 – 49.24)
$SR_2$ [mm]	3.59 (2.33 – 12.20)
$SP$	0.89 (0.85 – 0.95)
$LMAX_{stick}$ [mm]	32.50 (31.55 – 34.60)
$PMAX_{stick}$ [%]	13.47 (3.26 – 20.66)
$STR_1$ [mm]	13.09 (10.13 – 18.91)
$STR_2$ [mm]	10.74 (8.09 – 13.81)
$STR_3$ [mm]	9.25 (6.16 – 11.49)
$STR_4$ [mm]	8.20 (0.00 – 10.04)
$STR_5$ [mm]	7.25 (0.00 – 8.99)
$STR_6$ [mm]	6.47 (0.00 – 8.05)
$STR_7$ [mm]	5.77 (0.00 – 7.38)
$STR_8$ [mm]	5.06 (0.00 – 6.75)
$STR_9$ [mm]	4.39 (0.00 – 6.17)
$STR_{10}$ [mm]	3.73 (0.00 – 5.67)
$STR_{11}$ [mm]	3.07 (0.00 – 5.18)
$STR_{12}$ [mm]	2.14 (0.00 – 4.73)
$STR_{13}$ [mm]	1.17 (0.00 – 4.36)
DOF	44
Deviance	31.36
p-value	0.9238

## Norway lobster

Out of 683 Norway lobsters caught and length measured during the study, 612 were retained inside the test creels without sticking, 2 individuals were stuck in the



**Fig 5:** Mantis shrimp: experimental length dependent portioning of the catches (left column) and length dependent probability for retention inside the creel, sticking in the test creel meshes and escapement from the test creel (right column). The black solid circles represent the experimental catch rates according to equations (6); black curves in left column represent modelled probability according to equations (4); black curves in right column represent modelled probability according to equations (1); dashed lines represent 95% confidence intervals; A: catch proportion retained inside test creels; B: probability of retention inside the creel; C: catch proportion stuck in test creel meshes; D: probability of sticking in test creel meshes; E: catch proportion in control creels; F: probability of escapement from the test creels.

test creel meshes and 69 individuals were retained by the control creels. The number of individuals retained by the test and control creels on each fishing day is shown in tables 4 and 5, respectively.

The fit statistics for Norway lobster (Table 6) show that model describes well the length-based trend in the data, which is confirmed by the visual inspection of model fit to data (Fig. 7). The average SP value was not significantly different from the expected value of 0.89 [number of test creels fished (124) divided by total number creels fished (140)] (Table 6). Similar as for mantis shrimp, the sticking probability curve for Norway lobster is bell-shaped, but the sticking probability was not estimated to be significantly different from zero. This can be seen from the curve's 95% confidence intervals, where lower CI limit equals zero for all length classes (Fig. 7).

The maximum sticking probability was estimated to be 2.01 % for Norway lobster carapace length at 34 mm, but it was not significantly different from zero (95% confidence intervals of the estimated maximum sticking probability include zero).

## Discussion

Mediterranean creel fishery catch data were used as a case study to develop a modelling and estimation approach able to quantify the probability of mesh sticking as integral part of size selection estimation. Results were obtained for mantis shrimp and Norway lobster for creels with 41 mm square meshes. To our knowledge, this is the first study that quantifies the sticking probability in

**Table 4.** Number of Norway lobster individuals retained inside the test creel longlines (RT) and stuck in the meshes of test creel longlines (ST) on each fishing day; test deployment index [*i*]: test deployment indexes used in the inner summation of expression (5) (see Sistiaga *et al.* (2016) for details).

Date	Number of longlines	Test Deployment index [ <i>i</i> ]	RT	ST
26/05/2016	7	1 - 7	45	1
27/05/2016	7	8 - 14	46	0
28/05/2016	10	15 - 24	49	1
03/06/2016	8	25 - 32	40	0
04/06/2016	9	33 - 41	48	0
05/06/2016	8	42 - 49	32	0
07/06/2016	7	50 - 56	36	0
08/06/2016	8	57 - 64	25	0
14/06/2016	7	65 - 71	40	0
20/06/2016	6	72 - 77	41	0
22/06/2016	6	78 - 83	29	0
26/06/2016	7	84 - 90	28	0
29/06/2016	8	91 - 98	28	0
01/07/2016	10	99 - 108	42	0
03/07/2016	8	109 - 116	43	0
05/07/2016	8	117 - 124	40	0

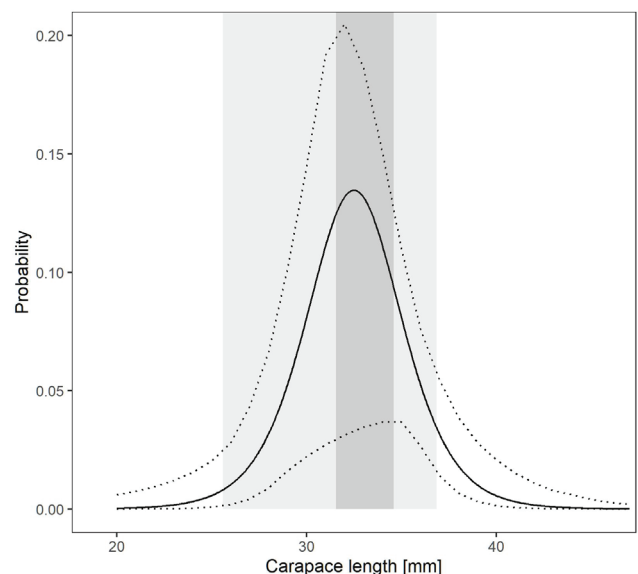
**Table 5.** Number of Norway lobster individuals retained by the control creel longlines (RC) on each fishing day; control deployment index [*j*]: control deployment indexes used in the inner summation of expression (5) (see Sistiaga *et al.* (2016) for details).

Date	Number of longlines	Control Deployment index [ <i>j</i> ]	RC
26/05/2016	1	1	3
27/05/2016	1	2	12
28/05/2016	1	3	5
03/06/2016	1	4	1
04/06/2016	1	5	2
05/06/2016	1	6	6
07/06/2016	1	7	3
08/06/2016	1	8	1
14/06/2016	1	9	5
20/06/2016	1	10	6
22/06/2016	1	11	2
26/06/2016	1	12	9
29/06/2016	1	13	2
01/07/2016	1	14	7
03/07/2016	1	15	4
05/07/2016	1	16	1

size selectivity studies. The method was inspired by the un-paired size selection estimation method described by Sistiaga *et al.* (2016). In this study, we modelled experimental data summed over longline deployments, for test and control creels. The model describes the experimentally observed length-dependent portioning of catches between compartments, enabling quantification of the length dependent probabilities of retaining inside the creel, sticking in the creel meshes and escaping from the test creels.

**Table 6.** Modelling results for Norway lobster;  $L50$  is the carapace length for Norway lobster that has 50% probability to pass the barrier ( $L50_1$  for barrier I and  $L50_2$  for barrier II in Fig. 2);  $SR$  denotes the difference in carapace length between Norway lobster with a 75% and 25% probability, respectively, passing the barrier ( $SR_1$  for barrier I and  $SR_2$  for barrier II in Fig. 2);  $SP$  is the probability that a Norway lobster will enter one of the test creels, on condition that it enters one of the creels (test or control);  $STR_x$ : the width of the size range where the sticking probability is at least  $x\%$ ;  $PMAX_{stick}$ : maximum sticking probability;  $LMAX_{stick}$ : carapace length at the maximum sticking probability; DOF: degrees of freedom.

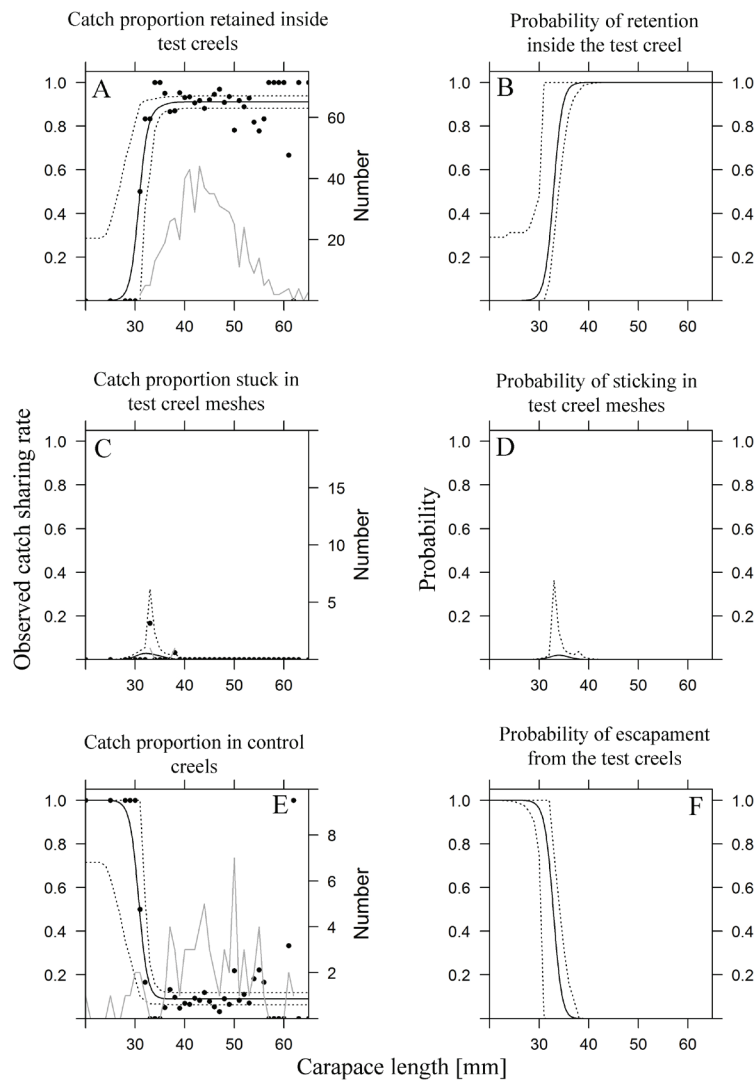
$L50_1$ [mm]	32.89 (30.61 - 34.02)
$SR_1$ [mm]	1.95 (0.10 - 3.07)
$L50_2$ [mm]	36.42 (32.52 - 196.44)
$SR_2$ [mm]	2.30 (0.10 - 3.74)
$SP$	0.91 (0.88 - 0.94)
$LMAX_{stick}$ [mm]	34.01 (1.00 - 38.15)
$PMAX_{stick}$ [%]	2.01 (0.00 - 37.01)
$STR_1$ [mm]	4.41 (0.00 - 6.86)
$STR_2$ [mm]	0.07 (0.00 - 4.57)
DOF	72
Deviance	44.28
p-value	0.9959



**Fig 6:** Probability of mantis shrimp sticking in the test creel meshes. Light grey band: 95% confidence intervals of the mantis shrimp  $L50$  estimated by Brčić *et al.* (2018a) without accounting for sticking; dark grey band: 95% confidence intervals of the carapace length at the maximum sticking probability for mantis shrimp from the present study.

The obtained bell-shaped sticking probability curve was expected, since only a specific range of crustacean lengths can get stuck in the creel meshes. Sticking probability curve differed between the two investigated species. Further, all mantis shrimps were stuck with their head protruding outside the creel, while Norway lobsters were stuck with their tail protruding outside the creel (Fig. 4), emphasizing the difference in escape behaviour between





**Fig 7:** Norway lobster: experimental length dependent portioning of the catches (left column) and length dependent probability for retention inside the creel, sticking in the test creel meshes and escapement from the test creel (right column). The black solid circles represent the experimental catch rates according to equations (6); black curves in left column represent modelled probability according to equations (4); black curves in right column represent modelled probability according to equations (1); dashed lines represent 95% confidence intervals; A: catch proportion retained inside test creels; B: probability of retention inside the creel; C: catch proportion stuck in test creel meshes; D: probability of sticking in test creel meshes; E: catch proportion in control creels; F: probability of escapement from the test creels.

these two species. Mantis shrimp is the species with the highest number of stickers observed and it is probably in relation to both, the species morphology and behaviour. The body shape of this species increases in width from carapace to telson, with short lateral and dorsal spines pointing backwards. Mantis shrimps are probably using these spines to gain purchase on the twine as they wiggle through the meshes, in the same manner as was theorized for the redfish by ICES (2012). In case where mantis shrimp is unable to escape through the meshes, the spines probably prevent it from returning inside the creel.

The results presented here are obtained for creels covered with square mesh netting. Regarding the sticking risk, square meshes are not very popular among fishermen, for example ICES (2012) reported that fishermen were not even interested in testing selectivity of square mesh codends in redfish trawl fishery because of the

sticking problem (ICES, 2012; Pol *et al.*, 2016). The legislation allows only square meshes for the investigated creel fishery (with 10% deviation from the perfect square shape), while the use of diamond meshes which might reduce sticking probability cannot be applied.

The method described in this paper could potentially be adopted for trawl fishery, especially when data are collected using paired (Krag *et al.*, 2014) or un-paired methods (Larsen *et al.*, 2018) using blinded control codends.

## Acknowledgements

The research leading to this paper was funded by the Croatian Ministry of Agriculture and Norwegian Research Council. We are grateful to Captain Ivo Tomaš for his help with the construction of control creels and for al-

lowing us to join him during his regular fishing trips. We would like to thank a crew member Marinko Ivandić for his valuable help during the fieldwork. We are also grateful to the Ingrid Čatić for the language revision and two anonymous reviewers for their suggestions, which helped us to improve the manuscript significantly.

## References

- Anonymous, 2011. Atlas of Demersal Discarding, Scientific Observations and Potential Solutions. Marine Institute, Bord Iascaigh Mhara. 82 pp.
- Anonymous, 2015. Pravilnik o obavljanju gospodarskog ribolova na moru mrežama stajaćicama, klopkastim, udičarskim i probodnim ribolovnim alatima te posebnim načinima ribolova. Narodne novine br.: 84.
- Arkley, 2001. *Improving Selectivity in Towed Fishing Gears - Guidelines on the Rigging of Square Mesh Panels*. SEAFISH, 24 pp.
- Brčić, J., Herrmann, B., Mašanović, M., Baranović, M., Šifner, S.K. *et al.*, 2018a. Size selection of *Nephrops norvegicus* (L.) in commercial creel fishery in the Mediterranean Sea. *Fisheries Research*, 200, 25-32.
- Brčić, J., Herrmann, B., Mašanović, M., Krstulović Šifner, S.K. *et al.*, 2018b. CREELSELECT-A method for determining the optimal creel mesh: Case study on Norway lobster (*Nephrops norvegicus*) fishery in the Mediterranean Sea. *Fisheries Research*, 204, 433-440.
- Chernick, M.R., 2007. *Bootstrap methods: a guide for practitioners and researchers*. Wiley, New York. 400 pp.
- Efron, B., 1982. *The jackknife, the bootstrap and other resampling plans*. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, 100 pp.
- Eriksson, S.P., 2006. Differences in the condition of Norway lobsters [*Nephrops norvegicus* (L.)] from trawled and creeled fishing areas. *Marine Biology Research*, 2, 52-58.
- Fryer, R., 1991. A model of the between-haul variation in selectivity. *ICES Journal of Marine Science*, 48 (3), 281-290.
- Hamer, D.J., Goldsworthy, S.D., 2006. Seal-fishery operational interactions: Identifying the environmental and operational aspects of a trawl fishery that contribute to by-catch and mortality of Australian fur seals (*Arctocephalus pusillus doriferus*). *Biological Conservation*, 130 (4), 517-529.
- Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. *Journal of Northwest Atlantic fishery science*, 44, 1-13.
- Hovgård, H., Lassen, H. 2000. *Manual on estimation of selectivity for gillnet and longline gears in abundance surveys*. FAO, FAO Fisheries Technical Paper No. 397, 84pp.
- ICES, 2012. *Report of the ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB)*. ICES CM 2012/SSGESST:07, 206 pp.
- Krag, L.A., Herrmann, B., Karlsen, J.D., 2014. Inferring Fish Escape Behaviour in Trawls Based on Catch Comparison Data: Model Development and Evaluation Based on Data from Skagerrak, Denmark. *PLoS ONE*, 9 (2), e88819.
- Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I. *et al.*, 2018. New approach for modelling size selectivity in shrimp trawl fisheries. *ICES Journal of Marine Science*, 75 (1), 351-360.
- Løkkeborg, S., 2011. Best practices to mitigate seabird bycatch in longline, trawl and gillnet fisheries-efficiency and practical applicability. *Marine Ecology Progress Series*, 435, 285-303.
- Pol, M.V., Herrmann, B., Rillahan, C., He, P., 2016. Impact of codend mesh sizes on selectivity and retention of Acadian redfish *Sebastes fasciatus* in the Gulf of Maine trawl fishery. *Fisheries Research*, 184, 54-63.
- Rahikainen, M., Peltonen, H., Pönni, J., 2004. Unaccounted mortality in northern Baltic Sea herring fishery-magnitude and effects on estimates of stock dynamics. *Fisheries Research*, 67, 111-127.
- Ridgway, I.D., Taylor, A.C., Atkinson, R.J.A., Chang, E.S., Neil, D.M., 2006. Impact of capture method and trawl duration on the health status of the Norway lobster, *Nephrops norvegicus*. *Journal of Experimental Marine Biology and Ecology* 339 (2), 135-147.
- Sistiaga, M., Herrmann, B., Grimaldo, E., O'Neill, F., 2016. Estimating the selectivity of unpaired trawl data: a case study with a pelagic gear. *Scientia Marina*, 80 (3), 321-327.
- Soldo, A., Cetinić, P., Dulčić, J., 1999. Catch of Norway lobster, *Nephrops norvegicus* (L.), with lobster pot of different mesh size in the eastern Adriatic. p. 281-287. In: Proceedings of the International Symposium on Responsible Fisheries & Fishing Techniques, Insko, 16 -19 June 1999. Poland.
- Weimerskirch, H., Capdeville, D., Duhamel, G., 2000. Factors affecting the number and mortality of seabirds attending trawlers and long-liners in the Kerguelen area. *Polar Biology*, 23 (4), 236-249.
- Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. *Manual of methods of measuring the selectivity of towed fishing gears*. ICES Cooperative Research Report No. 215., 132 pp.