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Escape, discard and landing probability of *Nephrops norvegicus* in the Mediterranean Sea creel fishery

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Abstract

Size selection in creel fishery consists of two processes: the first taking place in the creel on the seabed and the second made by the fisher on the vessel. However, no study has ever considered both processes when assessing the size selection in creel fisheries. This study presents a framework for including both and demonstrates it to predict the effect of mesh size and shape on the creel fishery targeting the Norway lobster (*Nephrops norvegicus)* in the Mediterranean Sea. For this specific fishery, we demonstrate that both processes play a role in the overall size selection. Furthermore, we predict an optimal creel mesh size, which potentially eliminates the second process taking place on the vessel, while maintaining high efficiency for the first process on the seabed for the targeted sizes of *Nephrops*. The approach here presented can be also applied to other creel fisheries.

Keywords: Creel size selection, *Nephrops norvegicus,* Mediterranean Sea, Fisher size selection

1. Introduction

Nephrops norvegicus (hereafter referred to as *Nephrops*) is a deep-sea burrowing decapod inhabiting the muddy bottoms (Hill et al. 1990; Johnson et al. 2013) of the northeast Atlantic and the Mediterranean Sea (Johnson et al. 2013). It is considered as one of the most valuable shellfish species in the Mediterranean Sea (Lolas et al. 2021). *Nephrops* is caught all over the Mediterranean Sea, mostly by bottom trawlers (Morello et al. 2009), with the majority of the catches occurring in the Ionian and Adriatic Sea (FAO-GFCM 2021). According to FAO (FAO 2020), *Nephrops* is overexploited in a large part of the Mediterranean Sea. The total catch of *Nephrops* in the Mediterranean Sea in 2019 was 2613 t, which is the lowest catch since 1950

(FAO-GFCM 2021). Besides trawls, *Nephrops* are also harvested by creels (Morello et al. 2009; Brčić et al. 2018a; Lolas et al. 2021; Petetta et al. 2021), passive fishing gears that attract *Nephrops* using the bait placed inside them. They are designed to allow an easy entry while making the escape difficult (Thomsen et al. 2010). Specifically, the meshes of the creels only enable escape of *Nephrops* that are sufficiently small to pass through the meshes.

Compared to bottom trawls, creels are known to have a low ecological impact (Eno et al. 2001; Adey 2007; Kopp et al. 2020) and on average catch larger *Nephrops* in a much better condition (Eriksson 2006; Ridgway et al. 2006), yielding little or no bycatch (Morello et al. 2009; Brčić et al. 2018a). By contrast, the *Nephrops* catch efficiency in creels is lower than in bottom trawls (Morello et al. 2009). Since the EU is encouraging alternative types of fishing methods that increase size and species selectivity or minimize the negative impact of fishing activities on the marine environment (Regulation (EU) No 1380/2013), creels present a valid alternative to bottom trawls. In the eastern Adriatic Sea (Croatian waters), fishers target *Nephrops* using the rectangular metal frame creels covered with 36 mm or 40 mm square mesh netting (Croatian Regulation NN 84/2015). The fishery is mainly conducted in the internal waters (channel area) from March to November, and each fishing vessel is allowed to fish with maximum 300 creels (Brčić et al. 2018a). They are deployed in a longline system, typically with 30 creels per longline, using small scale fishing vessels, and are usually retrieved after one or more days (Brčić et al. 2018a). The average duration of retrieval process of one longline is less than 15 min (Brčić et al. 2018a). During this short period of time, the fisher takes the catch out of each creel, sorts it, rebaits all creels and prepares them for the next deployment. During the catch sorting process, the fisher must quickly evaluate the size of each Nephrops to minimize the air and light exposure of each undersized *Nephrops* (MCRS = 20 mm carapace length CL; Council Regulation (EC) No 1967/2006) before returning it back to the sea alive, since *Nephrops* caught with creels is exempt from the landing obligation because of high survival rates (Commission

Delegated Regulation (EU) 2018/3036). This represents a second size selection process, operated by the fisher. However, this process could be avoided if the size selection of creels on the seabed is optimized with respect to a desired exploitation pattern. This demonstrates the importance of considering both the gear and fisher size selection when evaluating a fishery, as has been shown for trawls (Mytilineou et al. 2018; 2020; 2021a; 2021b). Therefore, these two selection processes should be considered when making management decisions regarding the gear regulations for a specific fishery. Hence, our main goal was to present a framework that includes both the gear and fisher size selection and use them to predict the effect of mesh size and shape on the creel fishery targeting *Nephrops* in the Mediterranean Sea.

2. *Material and methods*

2.1 Experimental design

The sea trials were conducted between the 5th of April and the 4th of July 2019 in the North Adriatic Sea (Figure 1) onboard a commercial small scale fishing vessel (LOA 5.60 m and engine power 22 kW). An observer followed the fisher during his usual fishing operation. The commercial creels deployed by the fisher were made of plastic-coated rectangular metal frame (length 700 mm, width 410 or 450 mm, depth 270 mm and Ø5 mm) mounted with a diamond mesh polyamide netting with opening angle of 90° to obtain a square mesh shape (hereafter referred as to test creels). The mean mesh size of the test creels was 34.89 ± 0.46 mm SD and the mean opening angle 82.15° ± 5.61° SD. On each fishing day, in addition to all test creels deployed by the fisher, a special permit was obtained for one control longline containing creels identical in size and design (Supplement; Figure S1), apart from being mounted with a smaller mesh size netting (hereafter referred as to control creels), following the methodology described in Brčić et al. (2018a). The mean mesh size of the control creels was 15.7 ± 0.47 mm SD and mean opening angle 85.50 ° ± 5.30 SD. The mesh size of both, test and control creels were measured with the OMEGA mesh gauge and the opening angle using the image analysis routine implemented in FISHSELECT software (Herrmann et al., 2013). Both types of creels had two conical entrances positioned opposite each other, with a hook in the middle for attaching the bait. All creels were baited with the same quantity of saddled seabream *Oblada melanura*. They were deployed in a longline system, with 29 to 40 creels attached to the mainline, and retrieved after one to four days, depending on the weather conditions. Upon retrieval, the fisher sorted the catch of each longline into two groups, one destined to be discarded and the other to be landed. The observer onboard the vessel recorded whether each *Nephrops* belonged to the discard or landing portion of the catch. The observer also measured their CL to the nearest mm and registered the count number for each 1 mm CL class.

2.2 Data analysis

2.2.1 Creel size selection

Due to relatively small catches per creel, the catch from one longline deployment was considered as the base unit in the subsequent analysis (Brčić et at. 2018a). Given that the experimental data collection included test and control creels and since there was no obvious way of pairing the data, test creel selectivity was estimated following the unpaired estimation methodology described in Brčić et al. (2018a). The analysis was performed separately for deployments with different soak times by minimizing the following expression with respect to parameters $\boldsymbol{v}_{creel}$ and *SP*:

$$-\sum_{CL}\left\{\sum_{i=1}^{a} nT_{CLi} \times ln\left(\frac{SP \times r_{creel}(CL,\boldsymbol{v}_{creel})}{SP \times r_{creel}(CL,\boldsymbol{v}_{creel}) + 1 - SP}\right) + \sum_{j=1}^{b} nC_{CLj} \times ln\left(1.0 - \frac{SP \times r_{creel}(CL,\boldsymbol{v}_{creel})}{SP \times r_{creel}(CL,\boldsymbol{v}_{creel}) + 1 - SP}\right)\right\} \qquad (1)$$

where v_{creel} is a vector of parameters describing the size selection model $r(CL, v_{creel})$, nT_{CLi} and nC_{CLj} represent the number of *Nephrops* of carapace length *CL* retained by *i-th* and *j-th* deployment from the total of *a* test and *b* control creel deployments, respectively. The probability that *Nephrops* of carapace length *CL* would enter either test or control creel was modelled using the split parameter *SP*, where *SP* represents the probability that *Nephrops* entered the test creel and *1-SP* represents the probability that it entered the control creel, conditioned that it entered one of them (Wileman et al. 1996). Given that creels were mounted with a single size mesh netting and based on the previous studies (Xu and Millar 1993; Winger and Walsh 2011; Brčić et al. 2018a; Olsen et al. 2019), we assumed that size selection in creels can be described using the following *logit* model:

$$r_{creel}(CL,\boldsymbol{v_{creel}}) = \frac{exp\left(\frac{ln(9)}{SR_{creel}} \times (CL - CL50_{creel})\right)}{1.0 + exp\left(\frac{ln(9)}{SR_{creel}} \times (CL - CL50_{creel})\right)} \quad (2)$$

where $\boldsymbol{v_{creel}}$ represents the vector of parameters $CL50_{creel}$ and SR_{creel}. $CL50_{creel}$ is the CL of a *Nephrops* that has a 50% probability of being retained by the test creel given that it entered it. SR_{creel} is the difference in the CL of *Nephrops* with a 75% and 25% probability, respectively, of being retained by the test creel, given that it entered it. The estimation of the average selectivity for the test creel with *logit* size selection model (2) requires finding the values of the parameters *SP*, $CL50_{creel}$ and SR_{creel} that minimize (1). Minimizing the expression (1) is equivalent to maximizing the likelihood for the experimental data.

The ability of the model to describe the experimental data was inspected visually and evaluated based on the *p*-value and model deviance versus the degrees of freedom (DOF). Fit statistics is considered to be poor when *p*-value <0.05 and deviance/DOF >>1. In case of poor fit statistics, the residuals were inspected to determine if this is due to structural problems or due to the overdispersion in the data (Wileman et al. 1996).

The double bootstrap method for unpaired data (Sistiaga et. al. 2016; Brčić et al. 2018a) was used to estimate the 95% confidence intervals for the size selection curve and the associated parameters. This method accounted for the within deployment variation in *Nephrops* size structure as well as for the between deployment variation in the availability of *Nephrops* on the fishing grounds and the between deployment variation in creel size selection. A total of 1000 bootstrap repetitions were conducted to calculate the 95% Efron percentile confidence intervals (Efron 1982) for the size selection curves and their parameters.

The analysis above was performed separately for deployments with different soak times. To determine if there is a length-dependent difference in retention probability ($\Delta r(CL)$) between deployments with different soak times (x, y), the delta method (Larsen et al. 2018, Mytilineou et al. 2020; 2021b) was used as follows:

$$\Delta r(CL) = r_x(CL) - r_y(CL) \qquad (3)$$

The $r_x(CL)$ and $r_y(CL)$ represent the retention probabilities obtained for deployments with x and y day soak time, respectively. Following Larsen et al. (2018) and Olsen et al. (2019), the 95% Efron confidence intervals for each $\Delta r(CL)$ were estimated based on the bootstrap population of results obtained for $r_x(CL)$ and $r_y(CL)$ as follows:

$$\Delta r(CL)_i = r_x(CL)_i - r_y(CL)_i \qquad (4)$$

where i represents the bootstrap repetition index (1 to 1000). Since the bootstrap file generated for each soak time was independent, it was possible to obtain a bootstrap file for the difference in retention probability for deployments with different soak times (Larsen et al. 2018; Olsen et al. 2019). The results of the delta method were visualized through delta plots (Larsen et al. 2018; Olsen et al. 2019). If the 95% Efron confidence intervals for the $\Delta r(CL)$ in the delta plot include 0.0, this would mean that there is no significant difference in the length-dependent retention probability between the two deployments with different soak times. In case this was true for all $\Delta r(CL)$, the data from all deployments, irrespective of the soak time, were pooled and an additional creel selectivity analysis on the pooled data was performed.

2.2.2 Fisher size selection

Once the catch retained by the creels of each longline is brought onboard the fishing vessel, the second selection process begins with the fisher sorting *Nephrops* into two groups: discard and landing. The data collected in this way can be treated as cover codend data (Wileman et al. 1996). Specifically, each *Nephrops* of *CL* discarded by the fisher was considered as an escapee, while each landed *Nephrops* was considered as retained. Hence, the data from each deployment contained information on the number of discarded and landed *Nephrops* of each *CL*. The analysis was then performed by minimizing the following expression:

$$\sum_{i=1}^{a+b}\sum_{CL}\left\{nL_{CLi} \times ln\left(r_{fisher}(CL,\boldsymbol{v_{fisher}})\right) + nD_{CLi} \times ln\left(1 - r_{fisher}(CL,\boldsymbol{v_{fisher}})\right)\right\} \quad (5)$$

where nL_{CLi} and nD_{CLi} represent the number of *Nephrops* of *CL* landed and discarded by the fisher, respectively, from *i-th* deployment, from the total of $a+b$ longline deployments. The following *logit* size selection model can then be fitted to the data to obtain a fisher size selection curve:

$$r_{fisher}(CL,\boldsymbol{v_{fisher}}) = \frac{exp\left(\frac{ln(9)}{SR_{fisher}} \times (CL - CL50_{fisher})\right)}{1.0 + exp\left(\frac{ln(9)}{SR_{fisher}} \times (CL - CL50_{fisher})\right)} \quad (6)$$

where $\boldsymbol{v_{fisher}}$ represents the vector of parameters ($CL50_{fisher}$ and SR_{fisher}). The $CL50_{fisher}$ represents the CL of a *Nephrops* that has a 50% probability of being landed by the fisher given that it has been retained by the creel. The SR_{fisher} is the difference in CL of a *Nephrops* with a 75% and 25% probability, respectively, of being landed by the fisher, given that it has been retained by the creel. Therefore, the estimation of the average fisher selectivity with the *logit* size selection model (6) requires finding the values of the parameters $CL50_{fisher}$ *and* SR_{fisher} that minimize (5). The ability of the model to describe the experimental data was inspected following the same procedure as described for the creel size selection models.

2.2.3 Estimating the experimental length-dependent escape, landing and discard probability

Inspired by the work of Mytilineou et al. (2018), once the creel and fisher size selection have been estimated, it was possible to combine these two sequential processes to model the overall size selection for *Nephrops* in the given creel fishery. Once *Nephrops* of *CL* enters one of the test creels, three outcomes are possible:

1) *Nephrops* can escape through creel meshes described by the probability P_{esc} $(CL,\boldsymbol{v_{creel}})$,

2) *Nephrops* can be retained by the creel but discarded by the fisher, described by the probability P_{disc} $(CL,\boldsymbol{v_{creel}}, \boldsymbol{v_{fisher}})$, and

3) *Nephrops* can be retained by the creel and landed by the fisher, described by the probability P_{land} $(CL,\boldsymbol{v_{gear}}, \boldsymbol{v_{fisher}})$.

All three probabilities were then, following Mytilineou et al. (2018), modelled as:

$$P_{esc}(CL,\boldsymbol{v_{creel}}) = 1.0 - r_{creel}(CL,\boldsymbol{v_{creel}})$$

$$P_{disc}(CL,\boldsymbol{v_{creel}},\boldsymbol{v_{fisher}}) = r_{creel}(CL,\boldsymbol{v_{creel}}) \times (1.0 - r_{fisher}(CL,\boldsymbol{v_{fisher}}))\,(6)$$

$$P_{land}(CL,\boldsymbol{v_{creel}},\boldsymbol{v_{fisher}}) = r_{creel}(CL,\boldsymbol{v_{creel}}) \times r_{fisher}(CL,\boldsymbol{v_{fisher}})$$

Once the length-dependent discard probability was estimated, the following set of discard indicators (Mytilineou et al. 2018; 2021b) were also estimated: LDp_{max} representing the *CL* of *Nephrops* where maximum discarding probability (Dp_{max}) occurs and DR_x representing the size range where discarding probability is at least *x%*, where *x = (5%, 25%, 50%, 75%, 95%).* For the details regarding the above-mentioned indicators, see Figure S2 in Supplement. The 95% Efron confidence intervals were estimated using the double bootstrap method as described previously in the text.

2.2.4 Predicting the escape, discard and landing probability with different creel mesh sizes and shapes

The estimated experimental escape, discard and landing probabilities are specific for the test creels used in the study. However, we were interested to find out how the escape, discard and landing probabilities would change if creels with different mesh sizes and mesh opening angles were used. Assuming that the average fisher size selection ($r_{fisher}\ (CL,\ \boldsymbol{v}_{\boldsymbol{fisher}})$) is constant, the CREELSELECT model developed by Brčić et al. (2018b) was used to predict creel size selection ($r_{creel}\ (CL, \boldsymbol{v}_{\boldsymbol{creel}})$) for different mesh sizes and mesh opening angles. As shown by Brčić et al. (2018b), this model was able to accurately reproduce the experimental *Nephrops* creel size selection obtained by Brčić et al. (2018a). In the present study, before making any predictions, we first tested the model to see if it was able to reproduce the experimentally obtained size selection curve for the test creels obtained in this study. The obtained values were then used in the model (see Eq. S1 and Table S1 in the supplementary material for the details of the model) to predict creel size selectivity. The predicted curve was then plotted together with the experimentally obtained size selection curve from this study to check if the predicted curve falls within the 95% Efron confidence intervals of the experimental curve. This would provide an additional validation of the CREELSELECT model which can be used with increased confidence to predict the creel size selection ($r_{creel}\ (CL, \boldsymbol{v}_{\boldsymbol{creel}})$) for *Nephrops*. The legislated mesh sizes in Croatian *Nephrops* creel fishery are 36 or 40 mm (depending on the region) and the deviation in mesh opening angle from the perfect square (opening angle =90°)

of ± 10% is tolerated. Therefore, the model was used to predict r_{creel} ($CL,\boldsymbol{v}_{creel}$) for mesh sizes ranging from 30 mm to 46 mm in steps of 2 mm and opening angles ranging from 60° to 90° in steps of 2°. These predictions were then used together with the experimentally obtained r_{fisher} ($CL,\boldsymbol{v}_{fisher}$) (assuming it is constant) in (6) to predict the length-based escape, discard and landing probability in creels for the selected combination of mesh sizes and mesh opening angles. Further, based on the predicted length-dependent discard probability curves, we calculated a maximum discarding probability (Dp_{max}) for each combination of mesh size and mesh opening angle. The calculated Dp_{max} values were then visualized in an iso- Dp_{max} plot.

2.2.5 Predicting the effect of creel mesh size and mesh opening angle on Nephrops exploitation pattern

To examine how applying different creel mesh sizes and opening angles would affect the exploitation pattern in the *Nephrops* creel fishery, the following set of indicators were calculated (Herrmann et al. 2021):

$$
\begin{aligned}
nP- &= 100 \times \frac{\sum_{CL<MCRS}\{r(CL,CL50,SR) \times nPop_{CL}\}}{\sum_{CL<MCRS}\{nPop_{CL}\}} \\
nP+ &= 100 \times \frac{\sum_{CL>MCRS}\{r(CL,CL50,SR) \times nPop_{CL}\}}{\sum_{CL>MCRS}\{nPop_{CL}\}} \qquad (7) \\
nDRatio &= 100 \times \frac{\sum_{CL<MCRS}\{r(CL,CL50,SR) \times nPop_{CL}\}}{\sum_{CL}\{r(CL,CL50,SR) \times nPop_{CL}\}}
\end{aligned}
$$

The *r(CL,CL50, SR)* represents the size selection curve obtained for a specific combination of the creel mesh size and mesh opening angle predicted using the CREELSELECT model (Brčić et al. 2018b). The $nPop_{CL}$ represents the population size structure of *Nephrops* encountered during the sea trials. In this study, the size structure of the *Nephrops* population retained by the control creel was used as $nPop_{CL}$. The *nP-* and *nP+,* respectively, quantify the percentage of *Nephrops* individuals retained by the test creels below and above the Minimum Conservation

Reference Size (*MCRS*) from the population of *Nephrops* encountered during the sea trials ($nPop_{CL}$). The *nDRatio* (discard ratio) quantifies the proportion of *Nephrops* under *MCRS* from the total catch retained by the test creels. According to the regulation (Council Regulation (EC) No 1967/2006), the *MCRS* for *Nephrops* is 20 mm CL. However, in case the fisher discards a certain portion of *Nephrops* above *MCRS* (indicated by $CL50_{fisher} > MCRS$), then substituting *MCRS* with $CL50_{fisher}$ in (7) allows finding the optimum combination of the creel mesh size and mesh opening angles that best match the exploitation pattern desired by the fisher. The preferred values of *nP-* and *nDRatio* are those close to 0% and of *nP+* those close to 100% as possible (Wienbeck et al. 2014; Sala et al. 2016; Brčić et al. 2018c; Kalogirou et al. 2019; Melli et al. 2020; Herrmann et al. 2021).

All the analyses were performed using the SELNET software (Herrmann et al. 2012; 2013). The statistical software tool R (version 4.1.1; R Core Team 2021) was used to produce plots using the metR (Campitelli 2021) and ggplot2 packages (Wickham 2016).

3. Results

A total of 7306 *Nephrops* were caught using 126 test and 15 control longlines during the 17 days of experimental fishing (Table 1). The longlines were deployed on the average depth of 77 m (±6.98 SD). The CL of retained *Nephrops* individuals ranged from 24 to 65 mm in test creels, and 17 to 59 mm in control creels. The mean number of individuals caught by test and control longlines were 52.9 (±13.6 SD) and 46.6 (±8.9 SD), respectively. The structure of the population caught in test and control longlines is shown in Figure S3 in Supplement.

To estimate the creel size selection for deployments retrieved after one (S1), two (S2), three (S3) and four (S4) days, we performed the analysis in two steps. The first step included fitting the logit curve (2) to the catch data. By visually inspecting the fit of the logit curve to experimental catch data for the control and test creels summed over all deployments (the catch sharing plot), it was noted that the fit was poor for the largest *Nephrops* length classes, confirmed by fit statistics in most cases. Therefore, in the second step, all *Nephrops* above 40.69 mm CL were excluded from the analysis. The cut-off point (=40.69 mm CL) was obtained by predicting the $CL99_{creel}$ (the CL of a *Nephrops* that has a 99% probability of being retained by the test creel given that it entered it) for the largest measured mesh size 36 mm + 2SD +10 mm and OA = 90° using the CREELSELECT model (Brčić et al. 2018b). This has been done to ensure that absolutely no *Nephrops* of that size could have escaped through the test creel meshes. After this step, a visual inspection of the fit to experimental data for deployments retrieved after one (S1), two (S2), three (S3) and four (S4) days indicated a good fit (Figure 2), confirmed by fit statistics (Table 2).

The 95% Efron confidence intervals in the delta plots (Supplement; Figure S4) included 0.0 in all cases, showing no significant difference in the length-dependent retention probability between deployments with different soak times. This allowed performing an additional analysis based on all deployments pooled together. The fit of the logit curve to the pooled experimental data (Figure 3) shows a good fit, confirmed by the fit statistics in Table 3. The estimated pooled $CL50_{creel}$ and SR_{creel} values, together with their respective 95% confidence intervals, are presented in Table 3. The estimated SP value is close to expected since there was a marked difference between the number of test and control creels deployed.

The fisher size selection was modelled using the logit size selection curve shown in Figure 4. The model reflected the trend in experimental data well. However, fit statistics (Table 3) potentially indicated that the model was inappropriate for describing the experimental data. Since no systematic patterns were observed after inspecting the residuals of the fit, the poor fit statistics was ascribed to the overdispersion in the data (Wileman et al. 1996). Therefore, we were confident in using this model to describe the fisher size selection. The estimated $CL50_{fisher}$ and SR_{fisher} values, together with their respective 95% confidence intervals, are presented in Table 3. The $CL50_{fisher}$ was significantly larger than $CL50_{creel}$ (no overlap between their respective 95% Efron confidence intervals) and the *Nephrops MCRS* (=20 mm CL).

The two sequential selection processes by the gear and the fisher were combined to model the overall size selection for *Nephrops* population entering the creel according to equation (6). Figure 5. shows the S-shaped curves for the escape and landing probability as well as a bell-shape discard probability curve. The left-hand side of the discard probability curve is defined by the probability of escaping from the gear on the seabed, while the right-hand side of the curve is defined by the fisher size selection. The maximum average discard probability of 83% was estimated for *Nephrops* CL 28.26 mm (Table 3), which is significantly larger than the *Nephrops MCRS* (=20 mm CL). The overall size selection combining the creel and fisher retention probability is represented by the landing probability (Figure 5).

To predict how the escape, discard and landing probabilities would change if creels with different mesh sizes and mesh opening angles were used, we first had to inspect if the CREELSELECT model (Brčić et al. 2018b) can accurately reproduce the experimentally obtained creel size selection obtained in this study. The mean mesh size (=34.89 mm) and mean opening angle (=82.15°) obtained from the creels used in experimental fishing in this study were applied in the CREELSELECT model to make a prediction that can be compared with the experimentally obtained size selection curve. The predicted curve falls within the 95% Efron confidence intervals of the experimentally obtained curve (Supplement; Figure S5), demonstrating that the CREELSELECT model can be used with confidence to predict *Nephrops* size selection in creels.

After validation, the CREELSELECT model was used to predict the creel retention probabilities for mesh sizes ranging from 30 mm to 46 mm in steps of 2 mm and opening angles ranging from 60° to 90° in steps of 2°. The predicted probabilities were then used together with the experimentally obtained fisher size selection probability to predict the length-dependent escape, discard and landing probability in creels for the selected combination of mesh sizes and mesh opening angles (Figure 6). From the Figure 6, it is evident that both mesh size and mesh opening angle influence the escape, discard and landing probability of *Nephrops* in creels.

The Figure 7 shows the predicted maximum discard probabilities for creels as a function of mesh size and opening angle. The plot can be used by fisheries managers to determine the right combination of mesh sizes and opening angles for achieving the acceptable discard probability. For instance, knowing that the legislation allows ±10% deviation from the perfect square shape (opening angle = 90°), from the Figure 7, it is evident that the largest mesh size allowed in Croatian waters (=40 mm) has a lower discard probability compared to the smallest mesh size allowed (=36 mm). This is confirmed by the iso plots (Figure 8) showing the predicted exploitation pattern indicators (*nP-, nP+, nDRatio*) for the same mesh sizes and mesh opening angles.

From the Figure 8, it is evident that the mesh size 36 mm with the opening angle 90° would retain all sizes of *Nephrops* (*nP+* > 99%) desired by the fisher (>$L50_{fisher}$). However, it would also capture a substantial amount of *Nephrops* below this size (*nP-* ≈ 20%) if exposed to a population structure similar to that obtained by the control creel in this study. Therefore, resulting discard ratio for this given mesh size and shape would be approximately 4%. The mesh size 40 mm with the opening angle 90° would retain almost all sizes of *Nephrops* (*nP+*

≈ 92%) desired by the fisher (≥$L50_{fisher}$) and only few below this size (nP- ≈ 1%). Therefore, the resulting discard ratio (*nDRatio*) would be <1%.

4. Discussion

This is the first study that investigates the overall size selection of creels in the Mediterranean *Nephrops* creel fishery considering both the gear and fisher size selection. The results from the study demonstrate that both processes should be considered as they influence the gear exploitation pattern. Therefore, the fisheries managers need to consider both processes when making decisions regarding the gear regulations for this specific fishery. The methodology used in this study has previously been applied in trawl fisheries (Mytilineou et al. 2018; 2020; 2021a; 2021b) and has the potential to be applied in other fisheries as well where the sorting process is done manually by the fisher, e.g. creel fisheries targeting snow crab (Winger and Walsh 2007; Olsen et al. 2019). Future selectivity studies should also consider fisher size selection, and the methods presented here demonstrate how this could be addressed. Therefore, the application of such method could potentially affect how size selectivity in such fisheries could be evaluated in the future. Regarding the results obtained for the specific fishery investigated in this study, the average $CL50_{creel}$ value obtained for the creels with the average mesh size 34.89 mm and the opening angle 82.15° was 26.9 mm (95% CI: 26.1-27.5). The low estimated SR_{creel} value of 1.24 mm and its narrow confidence intervals (95% CI: 0.62-1.70), as well as the narrow 95% CI of the $CL50_{creel}$ demonstrate a sharp and precise size selection on the seabed. This is expected since the netting is firmly mounted on the creel frame, avoiding a large variation of mesh opening angles as observed in some other creel shapes, such as conical creels (Herrmann et al. 2021). The consequence of having a sharp size selection means that a simple adjustment of mesh size can yield the desired change in the size selection and, therefore, the creel exploitation pattern.

Compared to the $CL50_{creel}$ = 31.8 mm (95% CI: 17.8–33.2) obtained by Brčić et al. (2018a) for the *Nephrops* creels with the 41 mm square mesh netting, the $CL50_{creel}$ obtained in this study was significantly smaller (i.e., there was no overlap between the 95% CIs). The $CL50_{creel}$ obtained in this study was significantly larger than the *Nephrops MCRS* (=20 mm CL), indicating a significant mismatch with the desired exploitation pattern. Although the $CL50_{creel}$ was significantly larger than *MCRS* and the CL of all *Nephrops* individuals retained by the test creels were above *MCRS*, discarding still occurred. The reason for discarding was not the regulation, since the estimated $CL50_{fisher}$ of 29.62 mm (95% CI: 29.46 – 29.77) was significantly higher than *MCRS*, but, according to the fisher (G. Peranić, pers. comm.), because of the low commercial value of small *Nephrops*. Catchpole et al. (2005) reported that *Nephrops* discarding is strongly influenced by market forces, unlike by quotas or *MCRSs*. The small estimated SR_{fisher} parameter value of 1.31 mm and its narrow confidence intervals (95% CI: 1.08 – 1.51) demonstrate a sharp and precise fisher size selection despite the limited time available to the fisher during creel retrieval to evaluate the size of each *Nephrops* before deciding whether they are going to be landed or discarded. It should be noted that fisher size selection in this study has been estimated for only one fisher and could differ among the fishers. Further, some variation in fisher size selection could potentially be observed throughout the fishing season, and depending on the market value of *Nephrops*.

The results obtained showed how the escape, discard and landing probability in creels depend not only on the mesh size but also on the mesh opening angle. However, within the opening angle range of 81° - 90°, falling within the ±10% deviation from perfect square mesh shape, the exploitation pattern (*nP+, nP-*) and discard indicators (*nDRatio*, Dp_{max}) were relatively constant. Some caution must be taken knowing that our predictions are based on the *Nephrops* size distribution found during the experimental fishing within a specific area and it can differ spatially and temporally throughout the Adriatic Sea.

The Croatian regulation (NN 84/2015) defines 36 mm or 40 mm square mesh as the minimum mesh size in the *Nephrops* creel fishery. Compared to 40 mm square mesh, our results predict that 36 mm mesh size retains more *Nephrops* below the desired fisher size ($CL50_{fisher}$ = 29.62 mm), resulting in a higher discarding ratio. The unwanted sizes of *Nephrops* could escape from the creels while on the seabed if a larger mesh size (40 mm) was used. This would decrease sorting time onboard the fishing vessel and the probability of unintended *Nephrops* mortality since the high air and sea surface temperatures during fishing impact the survival rate of discarded *Nephrops* (Campos et al. 2015; Albalat et al. 2016; Fox et al. 2020; García-De-Vinuesa et al. 2020). The released individuals are also at risk of being attacked by sea birds (Evans et al. 1994; Eskelund et al. 2019) and other predators on their way to the seabed. Furthermore, knowing the gear and fisher size selection allows fisheries managers to reduce the unwanted discarding practice and easily compare different technological solutions implemented in a fishery.

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Competing Interests statement

The authors declare there are no competing interests.

Data Availability statement

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Tables

Table 1. Number of creels and longlines deployed and number of *Nephrops* caught (N) in test and control creels on each fishing day.

Date	Configuration	Num of creels	Num of longlines	Soak time (days)	N
05 April 2019	test	266	8	2	418
	control	30	1	2	35
06 April 2019	test	266	8	1	402
	control	30	1	1	35
17 April 2019	test	266	8	1	402

18 April 2019	test	266	8	1	440
	control	30	1	1	54
20 April 2019	test	266	8	2	470
	control	30	1	2	49
30 April 2019	test	137	4	2	221
	control	29	1	2	36
01 May 2019	test	137	4	1	207
	test	129	4	3	187
	control	29	1	1	43
02 May 2019	test	266	8	1	428
	control	27	1	1	48
04 June 2019	test	266	8	1	389
	control	29	1	1	53
05 June 2019	test	96	3	1	130
07 June 2019	test	64	2	2	75
	test	169	5	3	268
	control	29	1	3	48
08 June 2019	test	266	8	1	397
	control	29	1	1	55
12 June 2019	test	266	8	4	428
	control	29	1	4	63
14 June 2019	test	266	8	2	434
	control	29	1	2	45
19 June 2019	test	266	8	4	434
	control	29	1	4	43
21 June 2019	test	266	8	2	396
	control	29	1	2	55
04 July 2019	test	266	8	2	468
	control	29	1	2	50

Table 2. Size selection parameters obtained for *Nephrops* in creels soaked for one (S1), two (S2), three (S3), four (S4) days soak time and logit model fit statistics. Values in () represent 95% Efron confidence intervals. *CL50*: CL at which 50% of the *Nephrops* are retained (mm); *SR*: selection range (mm); *SP*: split parameter; DOF: degrees of freedom.

	S1	S2	S3	S4
CL50	27.13 (25.82-27.95)	26.57 (25.13-27.86)	25.61 (25.11-28.20)	27.28 (25.59-27.81)
SR	1.57 (0.10-2.47)	0.98 (0.10-2.21)	0.1 (0.10-1.61)	1.1 (0.10-1.50)
SP	0.92 (0.91-0.94)	0.92 (0.91-0.94)	0.91 (0.90-0.93)	0.93 (0.89-0.96)
p-value	0.84	0.51	0.46	0.33
Deviance	9.65	15.27	13.9	17.81
DOF	15	16	14	16

Table 3. Creel size selectivity parameters, fisher size selectivity parameters, logit model fit statistics for creel and fishers size selection and discard indicators. DOF: degrees of freedom. Values in () represent 95% Efron confidence intervals. $CL50_{creel}$: CL at which 50% of the *Nephrops* are retained by the creel (mm); SR_{creel}: creel selection range (mm); *SP*: split factor; $CL50_{fisher}$: CL at which 50% of the *Nephrops* are retained by the fisher (mm); SR_{fisher}: fisher selection range (mm); LDp_{max} represents the CL of *Nephrops* (mm) where maximum discarding probability (Dp_{max}) occurs; DR_x represents the CL range (mm) where discarding probability is at least x%, where x = (5%, 25%, 50%, 75%, 95%).

Parameter	**Value (CI)**
$CL50_{creel}$	26.94 (26.10-27.49)
SR_{creel}	1.24 (0.62-1.70)
SP	0.92 (0.91 - 0.93)
$p\text{-value}_{creel}$	0.5991
Deviance_{creel}	15.91
DOF_{creel}	18

$CL50_{fisher}$	29.62 (29.46 - 29.77)
SR_{fisher}	1.31 (1.08 - 1.51)
p-value$_{fisher}$	<0.001
Deviance$_{fisher}$	138.53
DOF$_{fisher}$	43
$DR_{0.05}$	60.11 (55.71 - 66.32)
$DR_{0.25}$	39.54 (3492 - 45.26)
$DR_{0.50}$	26.55 (19.98 - 35.18)
$DR_{0.75}$	12.31 (0.00 - 25.10)
$DR_{0.95}$	00.0 (0.00 - 07.87)
Dp_{max}	0.83 (0.70 - 0.97)
LDp_{max}	28.26 (27.43 - 28.60)

Figure Captions

Figure 1. Map of the study area. The green dots represent test longlines while the red dots represent control longlines. The map was created using QGIS version 3.22.7., with basemaps from Google Satellite 2022.

Figure 2. Catch sharing and size selection curves (solid) with their respective 95% confidence intervals (dashed) for one (S1), two (S2), three (S3) and four (S4) day soak time.

Figure 3. Catch sharing and size selection curves (solid) with their respective 95% confidence intervals (dashed) for all soak times pooled together. Vertical grey dotted line represents *Nephrops* minimum conservation reference size (MCRS = 20 mm CL)

Figure 4. Fishermen size selection curve (solid black line) with 95% Efron confidence intervals (dashed black lines). Vertical grey dotted line represents *Nephrops* minimum conservation reference size (MCRS = 20 mm CL).

Figure 5. The length-dependent escape (solid green line), discard (solid red line), and landing probability (solid blue line) and their respective 95% Efron confidence intervals (dashed lines). Vertical grey dotted line represents *Nephrops* minimum conservation reference size (MCRS = 20 mm CL).

Figure 6. Predicted escape (green), discard (red) and landing (blue) curves for different mesh sizes and mesh opening angles. MS: mesh size; OA: mesh opening angle.

Figure 7. Iso-lines showing predicted maximum discard probability values for creels with different mesh sizes and mesh opening angles (OA). The solid black dot represents the maximum discard probability obtained for the experimental creels in this study.

Figure 8. Iso-lines showing predicted exploitation pattern indicator values (*np-, np+, nDRatio*) for a range of mesh sizes and opening angles. The black solid dots represent the indicator values obtained for the experimental creels in this study. Vertical dotted lines indicate the two legal mesh sizes (36 and 40 mm) allowed in the Croatian *Nephrops* creel fishery.

Figures

Figure 1.

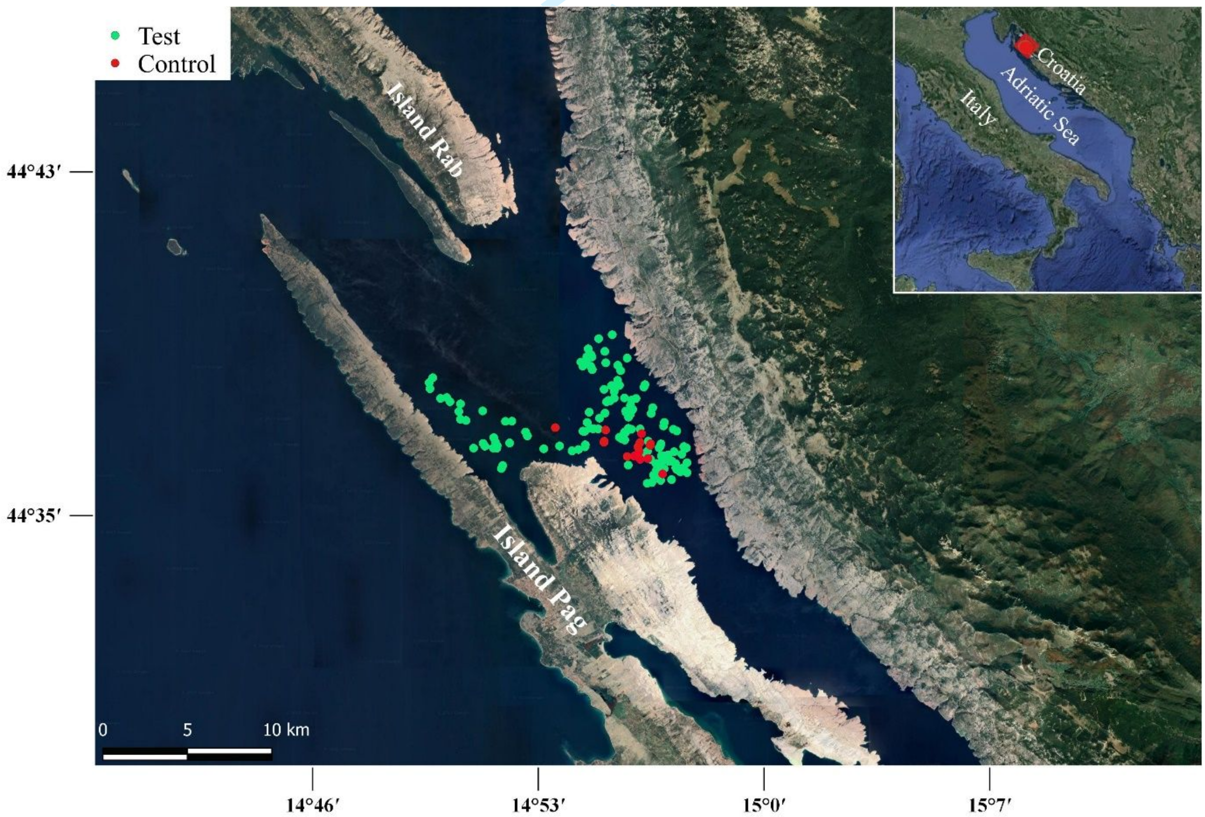


Figure 2.

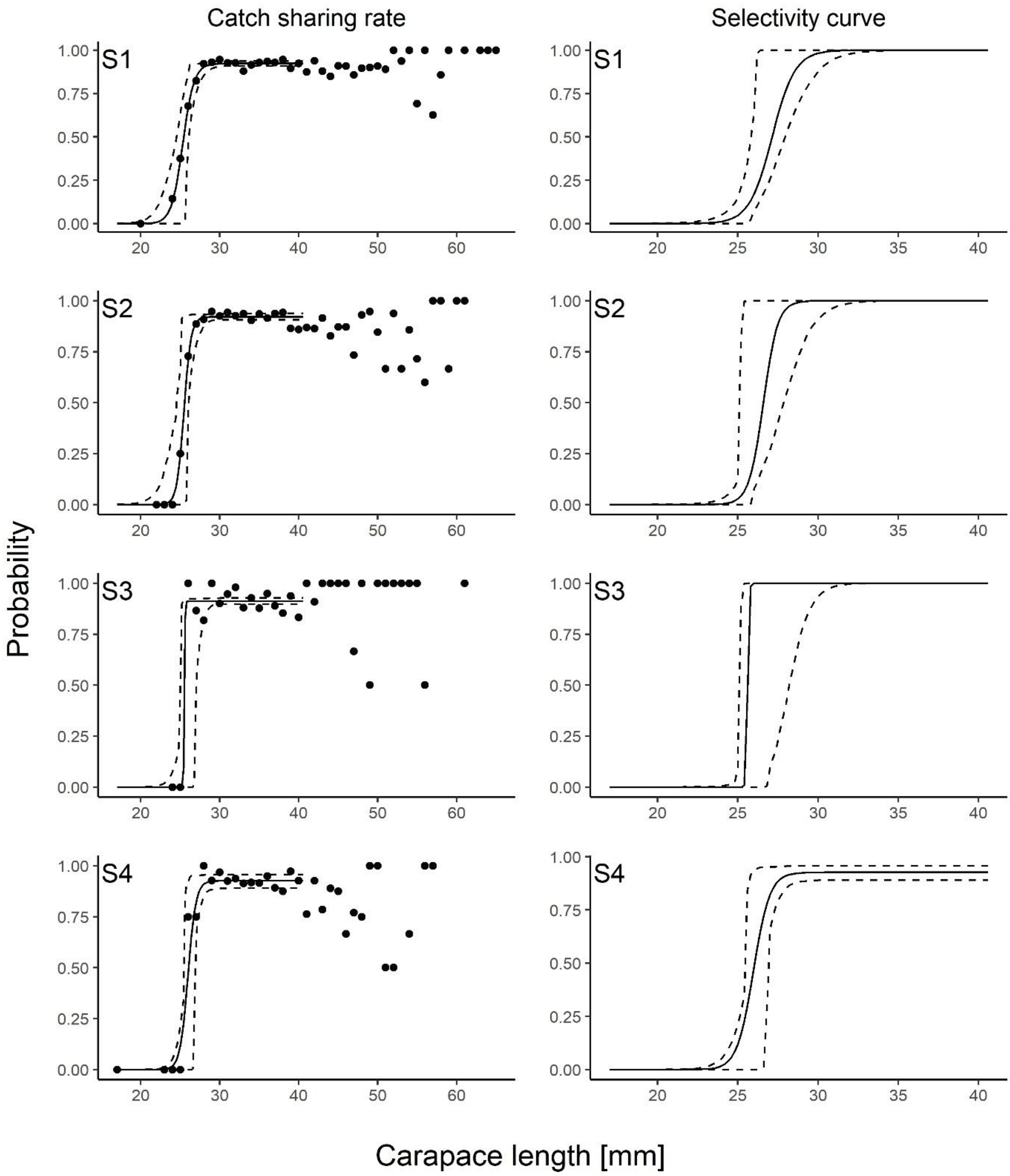

Catch sharing rate
Selectivity curve
S1
S2
S3
S4
Probability
Carapace length [mm]

Figure 3.

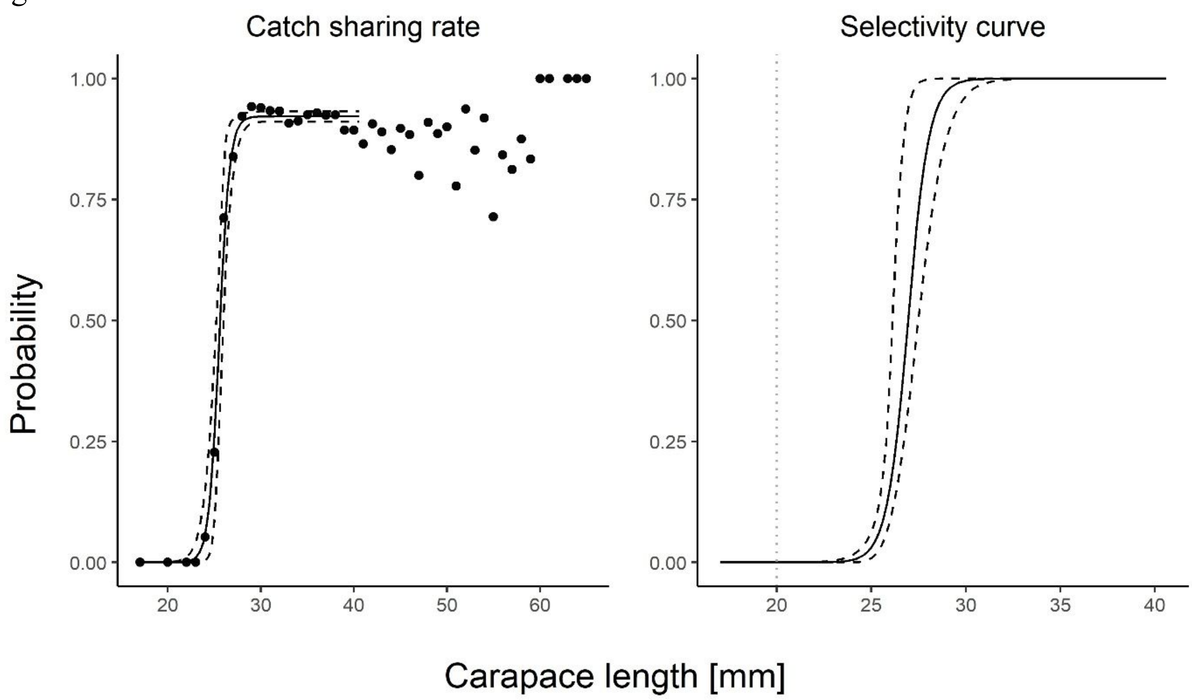


Figure 4.

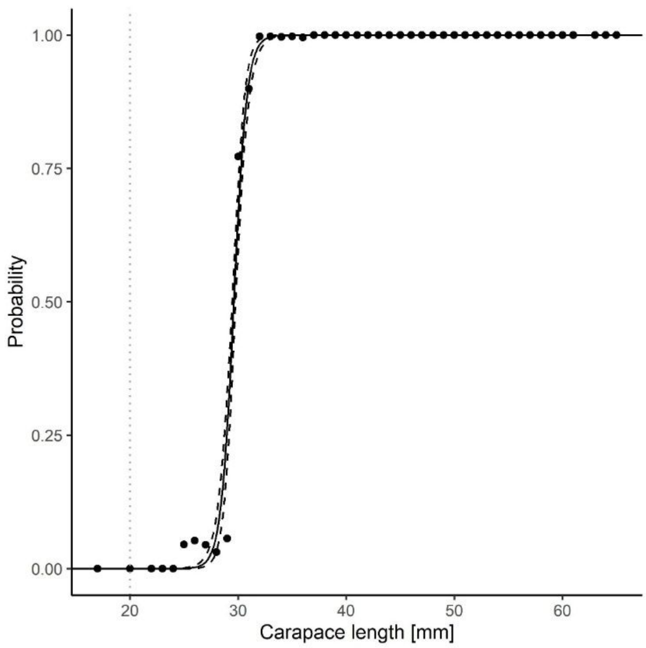


Figure 5.

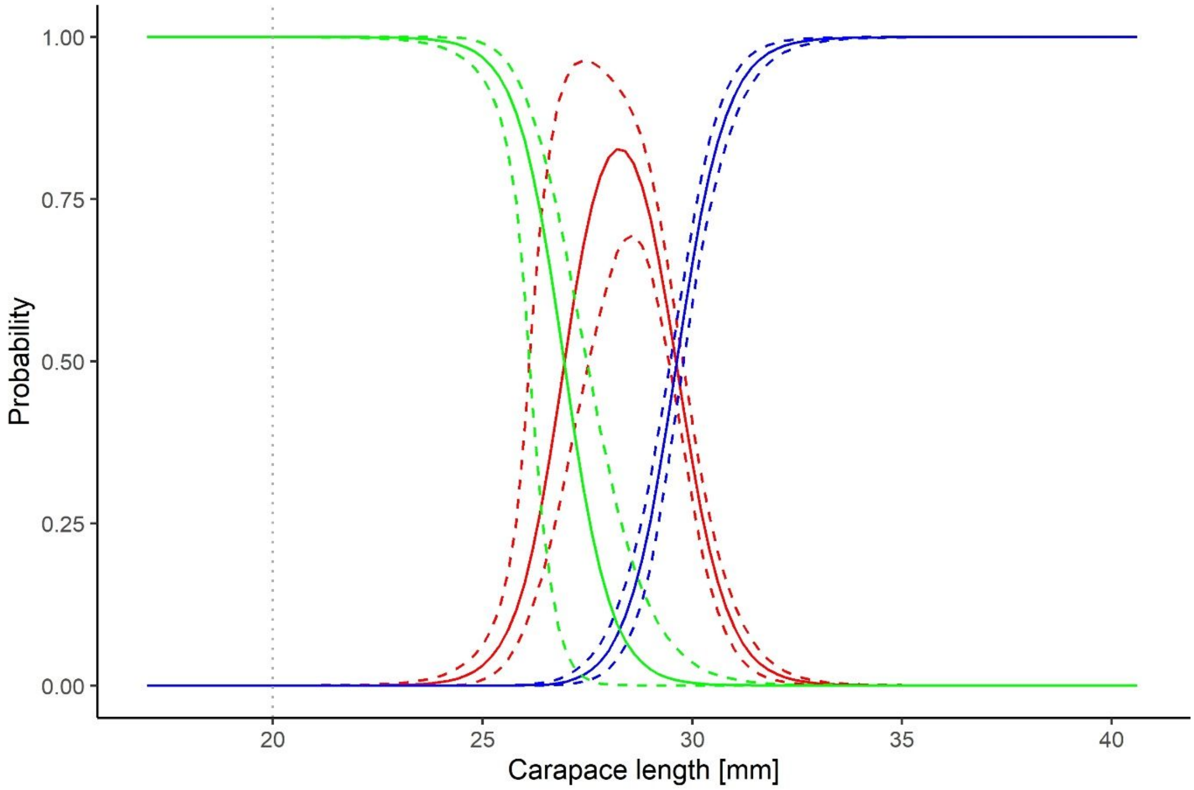

1.00
0.75
0.50
0.25
0.00
Probability
20
25
30
35
40
Carapace length [mm]

Figure 6.

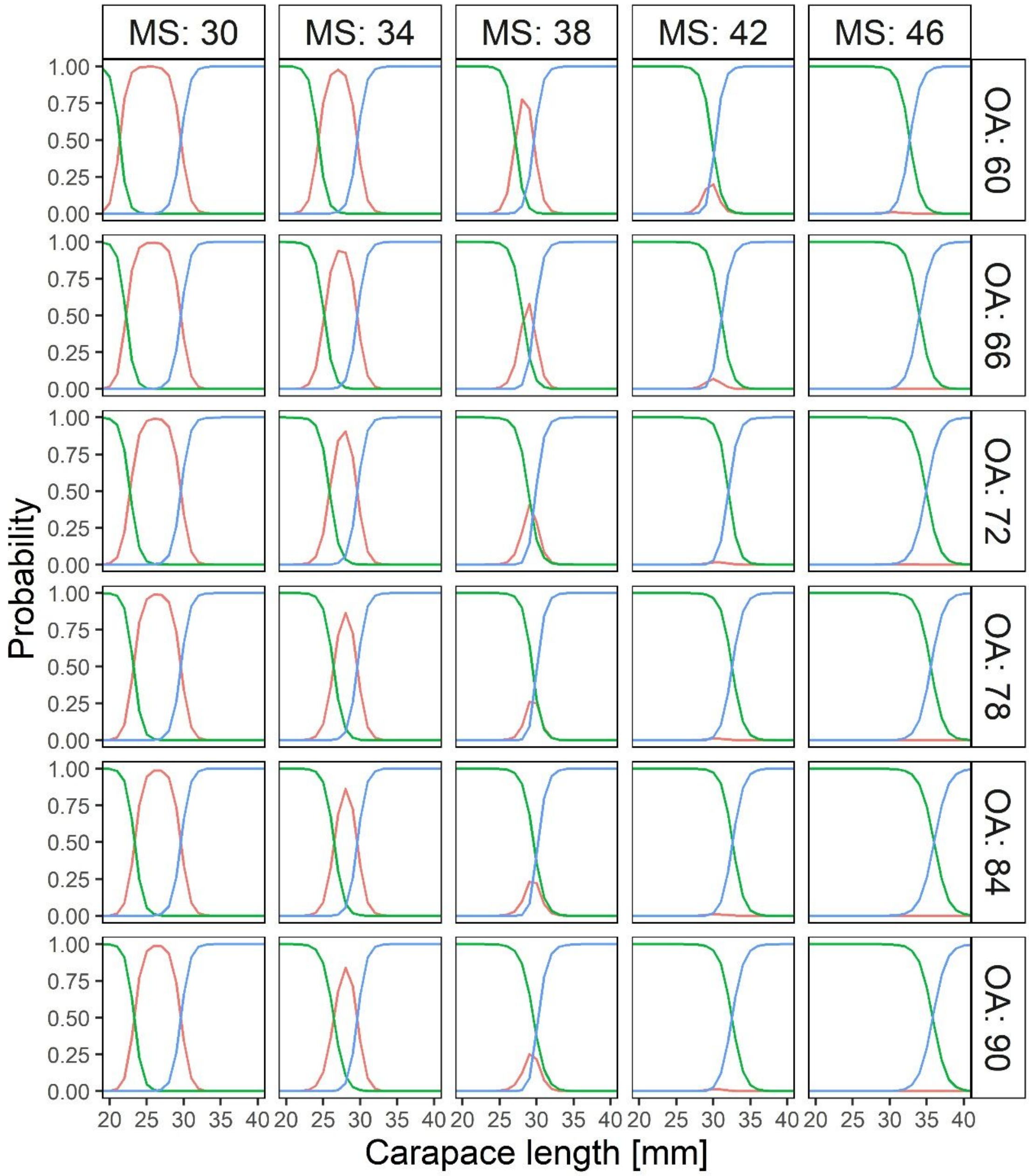

MS: 30
MS: 34
MS: 38
MS: 42
MS: 46
OA: 60
OA: 66
OA: 72
OA: 78
OA: 84
OA: 90
Probability
1.00
0.75
0.50
0.25
0.00
20 25 30 35 40
Carapace length [mm]

Figure 7.

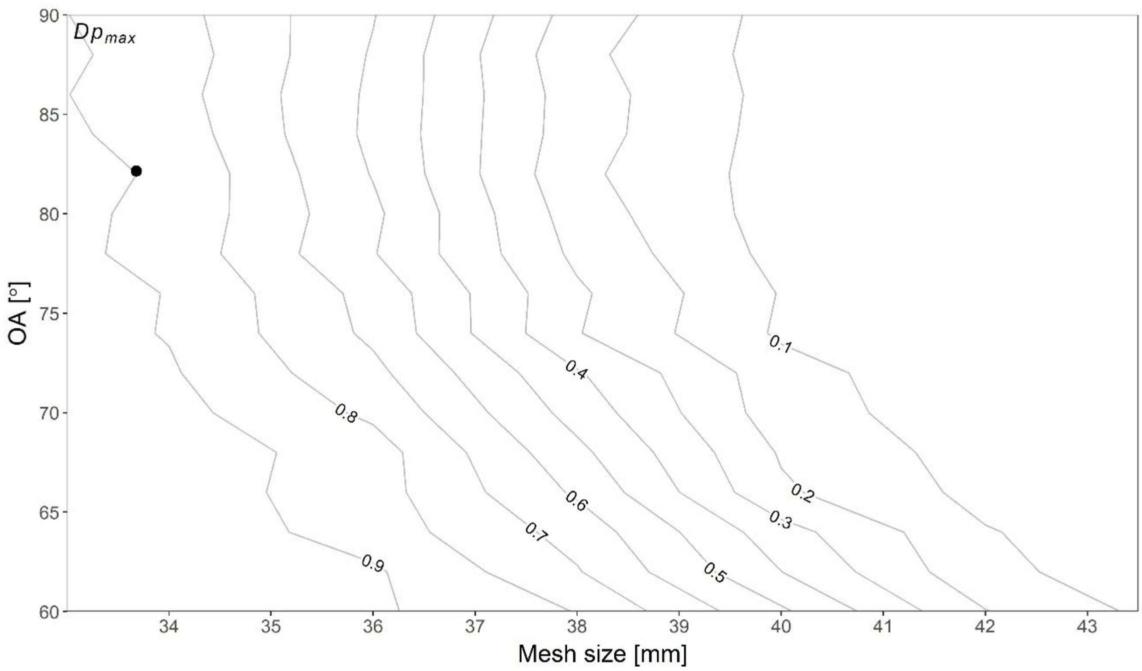
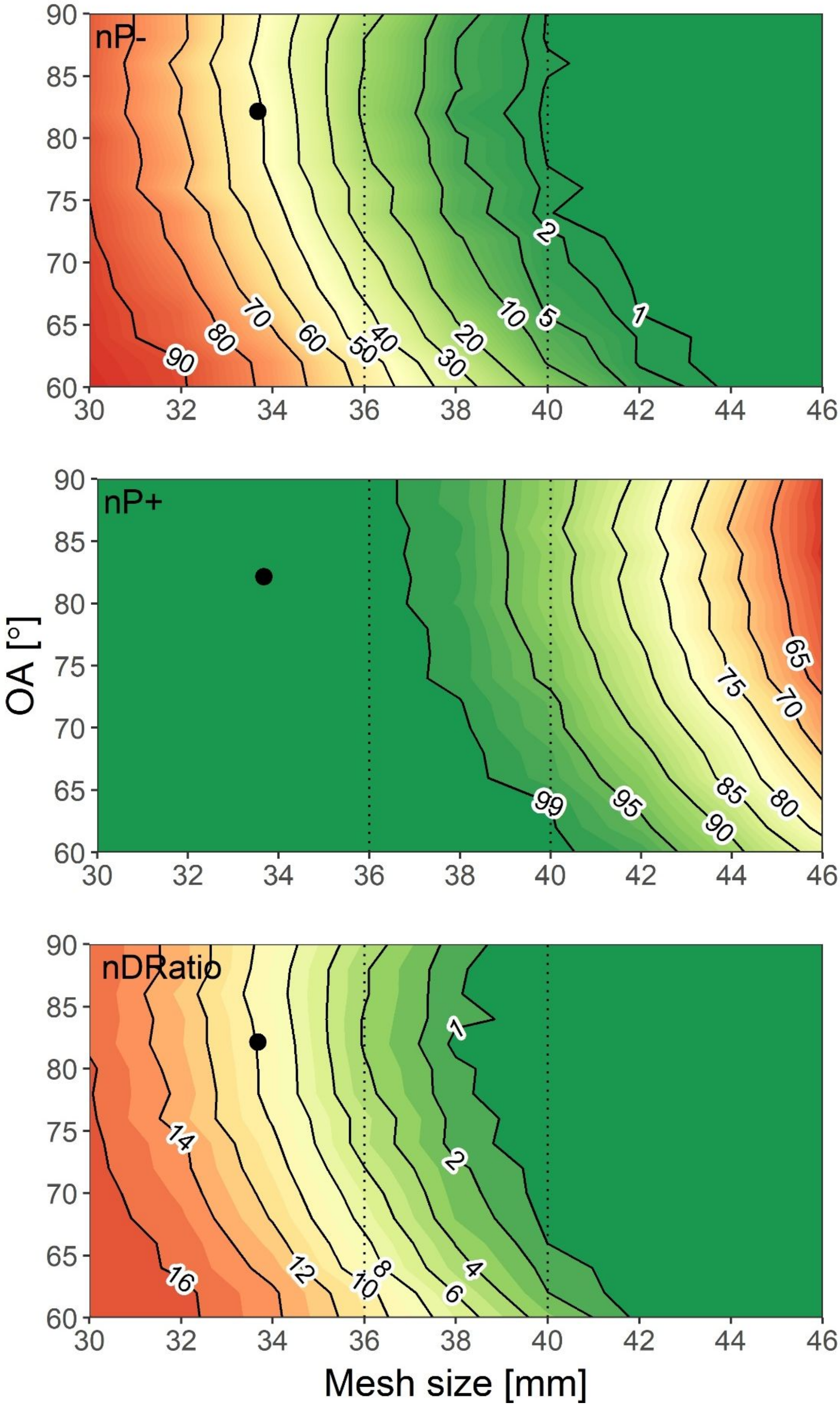

Dp_{max}
OA [°]
90
85
80
75
70
65
60
34
35
36
37
38
39
40
41
42
43
Mesh size [mm]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Figure 8.


nP-
nP+
nDRatio
OA [°]
Mesh size [mm]
90
85
80
75
70
65
60
30
32
34
36
38
40
42
44
46
90
80
70
60
50
40
30
20
10
5
2
1
99
95
90
85
80
75
70
65
16
14
12
10
8
6
4
2
1

712