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INSTITUTE OF OCEANOLOGY "PROF. FRIDTJOF NANSEN"

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TECHNOLOGICAL SOLUTIONS FOR REDUCING DISCARDS IN FISHERIES

AUTHOR'S ABSTRACT

of a

DISSERTATION

for the award of the educational and scientific degree

"Doctor"

Field of higher education:	4. Natural Sciences, Mathematics and Informatics
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The dissertation was discussed and referred for defence at an extended meeting of the Department of "Marine Biology and Ecology" at the Institute of Oceanology – BAS, held on 15 July 2026.

The dissertation has a total volume of 156 pages, of which 111 pages of main text, 22 pages of references and 23 pages of appendices; it contains 30 figures, 25 tables and 6 appendices. The list of cited literature includes 218 titles, of which 2 in Cyrillic, 201 in Latin script and 15 Internet sources.

The dissertation was prepared through part-time doctoral studies at the Institute of Oceanology – BAS.

The defence of the dissertation will take place on 06.11.2026 at 11:30 in the conference hall of the Institute of Oceanology at BAS, 40 "Parvi May" Street, at an open session of a Scientific Jury composed of:

Prof. Petya Pavlova Ivanova, PhD (IO, BAS)

Prof. Eliza Petrova Uzunova, PhD (Sofia University "St. Kliment Ohridski", Sofia)

Prof. Snejana Petrova Moncheva, PhD – retired (IO, BAS)

Assoc. Prof. Petar Georgiev Georgiev, PhD, Eng. (TU, Varna)

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The defence materials are available to interested parties in the library of the Institute of Oceanology "Prof. Fridtjof Nansen", Varna, 40 "Parvi May" Street.

INTRODUCTION

The Republic of Bulgaria, as a Black Sea country, is directly committed to the sustainable management of living marine resources. The Bulgarian Black Sea area represents a sensitive marine ecosystem subjected to the impact of anthropogenic pressure, climate change and intensive exploitation of fish resources. This determines the need to apply effective measures to limit the negative impact of fishing on marine ecosystems.

Among the main problems of contemporary fisheries are bycatch and the discarding of unwanted catch, which lead to additional fishing mortality and adversely affect the state of fish stocks. This problem is particularly pronounced in trawl fisheries, where insufficient selectivity of the gear used leads to the capture of undersized individuals and non-target species.

Improving the selectivity of fishing gear is one of the main approaches for limiting unwanted catch and reducing the impact on exploited populations. Selectivity allows the retention of predominantly the target size classes, while at the same time limiting the catch of immature and non-target organisms. For this reason, it is among the leading instruments for the sustainable management of fisheries and for meeting the contemporary requirements of the European fisheries policy.

In the Bulgarian waters of the Black Sea, the species *Mullus barbatus* (Linnaeus, 1758) (red mullet) and *Merlangius merlangus* (Linnaeus, 1758) (whiting) are of significant commercial interest. Despite their economic importance, experimental studies on the selectivity of the trawl gear used in the Bulgarian marine area are limited, which hampers the development of scientifically justified technical solutions for reducing bycatch and discards.

The present dissertation is devoted to investigating the possibilities for limiting discards by improving the selectivity of a conventional trawl used for catching demersal and near-bottom species in the Bulgarian Black Sea area. The study is based on experiments under real fishing conditions, analysis of the size structure of the catch and the application of contemporary statistical models for assessing the selective characteristics of the fishing gear.

The topicality of the study is determined by the need to reduce unwanted catch, to increase the sustainability of fishing activity and to overcome the shortage of scientific data on the selectivity of trawl gear in the Bulgarian Black Sea region. The scientific and practical significance of the study lies in the creation of an experimentally justified basis for optimizing the design of trawl gear and supporting the sustainable management of living marine resources.

LITERATURE REVIEW

The literature review shows that the selectivity of fishing gear is an established instrument for reducing bycatch and discards and for the sustainable management of fish resources. International studies demonstrate that improving selectivity reduces the fishing mortality of undersized and non-target organisms, improves the state of the stocks and supports the achievement of sustainable fisheries (Cook, 2003; Fauconnet, 2024; Broadhurst et al., 2006; Aranda et al., 2019).

The Black Sea is characterised by mixed fisheries, high exploitation of biological resources and vulnerable fish stocks. Published studies show that the trawl gear in use often does not provide the necessary selectivity, which leads to considerable bycatch and discards of juvenile and non-target species (Lleonart, 2005; Tsikliras et al., 2015; Raykov et al., 2021). At the same time, experimental studies aimed at optimising the selectivity of fishing gear in the Black Sea remain limited.

For the Bulgarian Black Sea area, the available scientific publications are few and predominantly fragmentary. Despite the application of the European regulations on technical measures, there is a lack of sufficient experimental data on the selectivity of the conventional trawl gear used in the capture of the main commercial species, including *M. barbatus* (red mullet) and *M. merlangus* (whiting). Standardised methodologies for assessing selectivity are also insufficient, as are practical recommendations for optimising the design of fishing gear.

The analysis of the literature sources shows the existence of a substantial scientific and applied gap related to the absence of systematic experimental studies on the selectivity of trawl gear in the Bulgarian Black Sea area. It is precisely this gap that determines the need for the present study, aimed at assessing the selective characteristics of a conventional trawl and developing scientifically justified solutions for limiting bycatch and discards.

AIM, TASKS AND SCIENTIFIC HYPOTHESIS OF THE DISSERTATION

Rationale for formulating the aim and the tasks

The analysis of the scientific literature, the regulatory framework and the existing studies shows insufficient experimental information on the operational selectivity of the conventional trawl gear used in the Bulgarian Black Sea area. There is a lack of scientifically justified data on the influence of the design characteristics of the codend on selectivity in the capture of the main commercial species – *M. barbatus* and *M. merlangus*, which determines the need for the present study.

Object of the study

The object of the study is the conventional trawl fishing gear used in the commercial capture of demersal and near-bottom fish in the Bulgarian Black Sea area.

Subject of the study

The subject of the study is the operational selectivity of trawl gear in the capture of *M. barbatus* and *M. merlangus* depending on the design characteristics of the codend and the fishing operation parameters.

Scientific hypothesis

It is assumed that the design characteristics of the codend, including mesh size and the mechanical properties of the netting twine, have a statistically significant influence on the operational selectivity of trawl gear. Optimising these parameters will increase the release of undersized individuals without substantially reducing the catch efficiency for the target size classes.

Aim of the dissertation

To assess the operational selectivity of conventional trawl fishing gear in the capture of *M. barbatus* and *M. merlangus* in the Bulgarian Black Sea area and, on the basis of experimental data and statistical analysis, to develop scientifically justified recommendations for improving selectivity and limiting unwanted catch.

Tasks of the dissertation

To achieve the stated aim, the following tasks have been formulated:

Task 1: To establish the design characteristics of the conventional trawl used for catching *M. barbatus* and *M. merlangus* in the Bulgarian Black Sea fishery, as well as the characteristics of the netting materials used.

Task 2: To assess the operational selectivity of the conventional trawl fishing gear used for catching *M. barbatus* and *M. merlangus* in the Bulgarian Black Sea fishery, and to determine the main parameters of their selectivity with respect to the retention and release of the different size classes of the target species.

Task 3: To develop an experimental design for the comparative assessment of selectivity under different design characteristics of the codend, including different mesh size and different stiffness/elasticity of the netting twine.

Task 4: To plan and carry out experimental hauls under real fishing conditions in order to collect data on the size structure of the retained and released specimens of *M. barbatus* and *M. merlangus*.

Task 5: To calculate and analyse the selectivity parameters, including the selection curve, the retention probability at different lengths, the minimum retention lengths and the corresponding indicators of operational selectivity.

Task 6: To apply statistical modelling in order to assess the influence of the design characteristics of the codend and the operational parameters on the selectivity of the fishing gear studied.

Task 7: To compare the results from the different design variants of the conventional trawl in order to identify the design characteristics that have the most substantial influence on the release of undersized individuals and the reduction of unwanted catch.

Task 8: To assess the correspondence between the established selectivity parameters and the minimum conservation reference sizes for the species studied, as well as the applicability of the results obtained in the context of the technical measures for the sustainable management of fisheries.

Task 9: To formulate scientifically justified recommendations for the application of trawl fishing gear with specific design and technical characteristics, aimed at improving operational selectivity, reducing discards and effectively applying the ecosystem approach in the management of the fishery for demersal and near-bottom species in the Bulgarian waters of the Black Sea.

Methodological framework

The study includes analysis of the design characteristics of the trawl gear, experimental hauls under real conditions, measurement of the catch, quantitative assessment of selectivity and statistical modelling of the selective characteristics of the different codend variants.

Expected results

It is expected that an experimentally justified assessment will be obtained of the operational selectivity of a conventional trawl under different design variants of the codend, and that the parameters with the most substantial influence on the release of undersized fish will be determined. The practical value of the study lies in the development of recommendations for improving selectivity, limiting bycatch and discards and supporting the sustainable management of fish resources in the Black Sea.

MATERIAL AND METHODS

MATERIAL

For the purposes of the present study, data were collected from real fishing operations carried out in the Bulgarian Black Sea area during the period 2021–2023, within

the geographical limits between 42°10′ – 43°00′ north latitude and approximately 27°60′ – 28°20′ east longitude, within the continental shelf along the western coast (Figure 4.15).

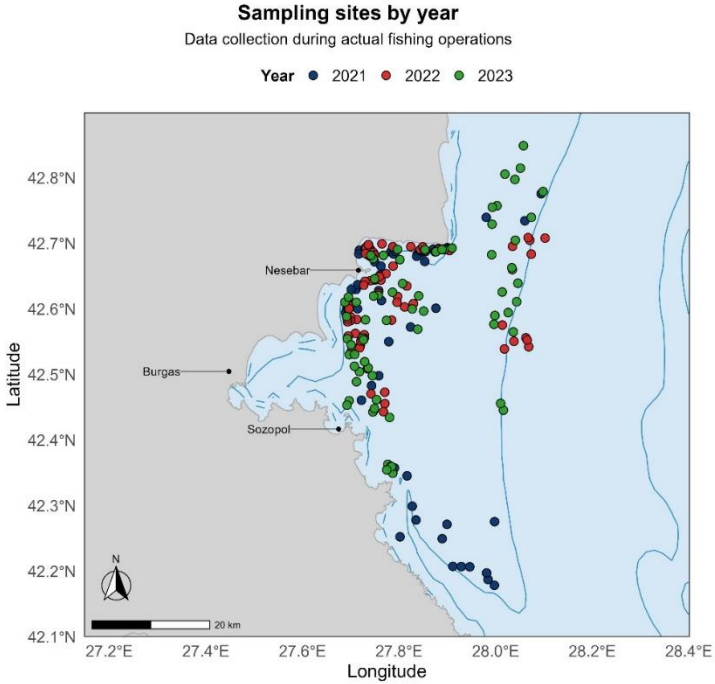


Figure 4.15. Spatial geographical distribution of the sampling sites by year (2021–2023), carried out during real fishing operations in the Bulgarian Black Sea area.

Bathymetrically, the area studied falls within the limits of the Bulgarian continental shelf, where the main part of the commercial trawl fishery is concentrated. The selected depth range (20–70 m) corresponds to the spatial distribution and feeding migrations of *M. merlangus* and to the bottom-associated character of *M. barbatus*. A total of 299 species-specific samples were collected and analysed, including 185 samples of *M. barbatus* and 114 samples of *M. merlangus* – a total of 36 241 individuals were measured, of which 23 328 specimens of *M. barbatus* and 12 913 specimens of *M. merlangus*.

The present analysis is based on data from real hauls, and the estimated selectivity should be interpreted as the effective (operational) selectivity of the trawl under real fishing conditions. In this context, the selectivity parameters (e.g. $L_{50\%}$ and SR) do not reflect solely the geometrically determined probability of fish passing through the mesh, but represent an integrated result of the interaction between the design characteristics of the gear and the operational factors, such as codend loading, towing speed and towing duration.

The inclusion in the complex model of operational factors related to the mechanical conditions of towing makes it possible to account for the influence of netting-panel deformation on the effective mesh opening, which determines the realised retention capacity of the codend.

For each haul, the initial and final geographical coordinates (WGS 84), working depth, towing duration, towing speed, the codend mesh size used and the total quantity of

the catch (in kg) were recorded. Subsamples of the target species were processed from each haul. Individuals were measured for total length (in cm) and individual weight (in g), the number of specimens analysed being consistent with the recommendations in the specialised literature for a reliable assessment of trawl gear selectivity (a minimum of 50 specimens, a statistically acceptable sample of 80–100 specimens and a recommended sample size of 120–150 specimens) (Millar, 2010; Herrmann et al., 2016; Sistiaga et al., 2016; Jacques et al., 2025; Moussa et al., 2026).

The analysis considers the overall selectivity of the trawls with respect to the two main near-bottom species – *M. merlangus*, the Black Sea whiting, and *M. barbatus*, the Black Sea red mullet; for this reason the composition of the bycatch of other biological species is not the object of consideration in the present study.

In the experimental hauls the catch was of a mixed character. Alongside the two species studied — Black Sea red mullet (*M. barbatus*) and whiting (*M. merlangus*) — accompanying catch of other demersal, near-bottom and pelagic fish and invertebrate organisms was recorded.

During the preliminary planning of the experiment, the vessels with which the data were collected were selected so as to be operational with twine characteristics and mesh size within the range of those most commonly used in the fishery of interest for the present dissertation.

At the stage of planning and design of the experiment, for the purposes of a justified data collection for the selectivity assessment and the application of the complex model for assessing the operational selectivity of the gear used under real fishing conditions, two types of parameters were identified: constants and variables in the codend selectivity model (Table 4.7 and Table 4.8).

Table 4.7. Constants (codend-specific parameters), valid for all gears used for the collection of data for the assessment of operational selectivity

Parameter	Notation	Description	Role in the model
Nominal mesh size	(d), *mm*	Mesh size in the codend of the trawl	Determines the basic geometry and the selectivity of the gear
Netting material of the codend	–	PA or PE	Determines the base modulus of elasticity
Twine diameter	–, *mm*	Actual diameter of the twine	Affects deformation
Effective cross-section	$(A(t))$ (mm^2)	Cross-section of the netting twine. It represents the load-bearing area of the twine and determines its resistance to tension. In the model it is taken as a design constant (if wear is not accounted for).	Participates in the stiffness of the netting element

Parameter	Notation	Description	Role in the model
Dyneema share	(f)	Relative share of Dyneema fibres in the load-bearing structure of the codend netting. Reflects the degree of reinforcement of the codend netting of the trawl	Increases the structural stiffness
Modulus of elasticity (E)) – effective modulus of elasticity	(E_{eff} (MPa))	Equivalent modulus of elasticity of the codend netting panel, accounting for the material and possible Dyneema reinforcement: $E_{eff} = (1 - f)E_b + fE_D$, where E_b is the base modulus of elasticity of the material, and E_D is the modulus of elasticity of a Dyneema-type twine	Determines the structural stiffness of the mesh

Table 4.8. Operational variables – parameters that change with every trawl operation (collected during the performance of the hauls)

Parameter	Notation	Description	Role in the model
Towing speed	(v)	Towing speed (mean towing speed)	Determines the hydrodynamic loading
Catch weight	(w)	Weight of the catch in the codend at the end of the haul and hauling of the catch on board the vessel	Increases the tensile loading of the codend netting
Towing duration	(τ)	Towing time	Determines the time-dependent deformation of the codend
Warp tension	$T(v, w)$	Warp tension	Affects the closing of the mesh
Engineering strain	ε_τ	A function of towing time and the characteristics of the material	Reflects the accumulated deformation

Characteristics of the fishing vessels with which the experimental data were collected:

1. FV "ISHTAR" Ns 1182 *(Image 4.7), MMSI: 207833240; Call sign: LZH3324; Flag: Bulgaria [BG]; Tonnage: 22.66 GT; Length overall × beam: 12.00 m × 5.8 m; Crew: 2; Power: 132.39 kW; CFR*: BGR002121182*



Image 4.7 Photograph of FV "ISHTAR"

2. FV "NIKO" Bs 152 *(Image 4.8), MMSI: 207822580; Call sign: LZH2258; Flag: Bulgaria [BG]; Tonnage: 20.37 GT; Length overall × beam: 15.70 m × 5.2 m; Crew: 3; Power: 264.78 kW; CFR*: BGR002020152*

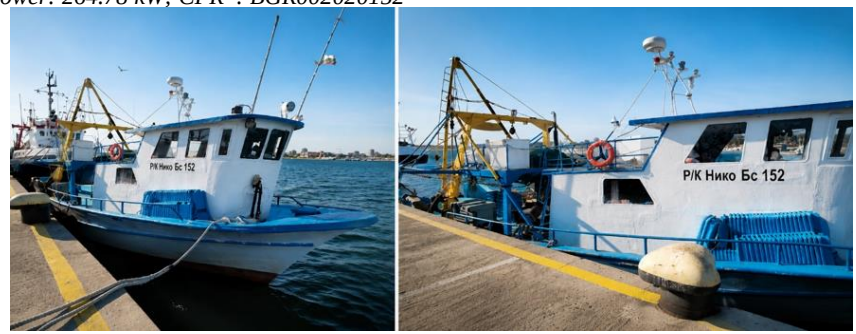


Image 4.8 Photograph of FV "NIKO" Bs 152

3. FV 5 Vn 8186 *(Image 4.9), MMSI: 207829480; Call sign: LZH2948; Flag: Bulgaria [BG]; Tonnage: 24.91 GT; Length overall × beam: 14.90 m × 4.4 m; Crew: 2; Power: 220.00 kW; CFR*: BGR001028186*



Image 4.9 Photograph of FV 5 Vn 8186

The overall design of the fishing gear used corresponds to Figure 4.6 – Detailed diagram of the construction of a conventional trawl for catching demersal and near-bottom species (*M. barbatus* and *M. merlangus*) – presented in Chapter IV of the present dissertation. The main differences between the gears used are the mesh size, the twine material and the resulting specific characteristics of the twine in operation.

Constants (codend-specific parameters) for the gears used for the collection of data for the operational assessment of selectivity

The constants for the gears used during the data collection, according to the technical information provided by the operators and to published information from the manufacturers, are presented in Table 4.9.

Table 4.9. Design and material characteristics of the codend determining the effective mesh opening d_{eff} and the selectivity of the trawl.

Codend (Conditional designation also adopted in the data analysis)	***Material of the codend***	***Mesh size (mm)***	***Twine diameter (mm)***	***(A(t)) (mm²)***	***Share of Dyneema in the codend twine (f)***	***E_{eff} (MPa)***
Trawl 1 FV "ISHTAR"	PA	32	2.6	5.31	0	1 200
Trawl 2 FV 5 Vn 8186	PE + Dyneema (UHMWPE)	34	2.4	4.52	0.15	18 080
Trawl 3 FV "NIKO"	PA	36	3	7.07	0	1 200

METHODS

Basic mathematical model of selectivity

The selectivity curve $S(l)$ or logistic curve (gear selection ogive) represents the probability with which a specimen of length L that has reached the codend will be retained and will not be released through the netting. It is described by the following formula (Sparre and Venema, 1998) and takes values in the interval [0,1]:

$$S(l) = \frac{1}{1+exp(S1-S2*L)} = \frac{1}{1+exp(a-b*L)}, \quad (1)$$

where:

$S(l) = \frac{number\ of\ specimens\ of\ length\ L\ in\ the\ codend}{number\ of\ specimens\ of\ length\ L\ in\ the\ codend\ and\ in\ the\ cover\ bag}$, and L is the mean length determined between two adjacent size classes, and $S1$ and $S2$ are constants ($S1 = a$, and $S2 = b$), which determine the shape and the position of the logistic curve (Fig. 1.4.2) (Paloheimo and Cadima, 1964; Kimura, 1978; Hoydal et al., 1982).

Complex model of selectivity

The complex mathematical model presented and proposed in the present dissertation was developed in accordance with the recommendations and the methodology proposed in a number of publications and manuals for the assessment of fishing gear selectivity (Fryer, 1991; Wileman et al., 1996; Millar & Fryer, 1999; Priour, 2003; Sala et al., 2007; O'Neill and Hermann, 2007); Grimaldo et al., 2008; Frandsen et al., 2010; Herrmann et al., 2012; Herrmann et al., 2012; Sala et al., 2015; De la Prada & González, 2015; Herrmann et al., 2016; Morvan & Priour, 2016; Sala et al., 2016; Herrmann et al., 2017; Cuende et al., 2020; Brooks et al., 2022; Brinkhof et al., 2022) and serves for the direct determination of operational selectivity from experimental data from fishing operations.

The starting point is the basic mathematical model – equation (1), which is elaborated through the inclusion of design characteristics and operational factors:

$$d_{eff}(x) = d * h^{k_1} * cos^{k_2}(\varphi) * \exp(-\eta_1 * \frac{T(v,w)}{E*A(t)} * \exp(-\eta_2 * \varepsilon_\tau(\tau; E, \eta)),$$

(22)

where:

d – nominal mesh size in mm;

$h \in (0,1]$ – hanging ratio (dimensionless quantity), φ – mesh opening angle (°);

k_1 and k_2 – exponents – calibrated for the gear used (estimated analytically by approximations);

$T(v,w)$ – the tensile stress in the warp as a function of the towing speed (v) and the catch weight (w)) – $T(v,w) = T_0 + k_v * v^2 + k_w * w$;

E – modulus of elasticity, $A(t)$ – effective cross-section of the twine, mm2;

η_1 – coefficient of sensitivity to elastic deformation;

$\varepsilon_\tau(\tau; E, \eta)$ – engineering strain of the twine, as a function of towing duration, the modulus of elasticity and the sensitivity to elastic deformation:

η_2 – dimensionless coefficient reflecting the sensitivity of the effective mesh opening to the towing duration;

Parameterisation with respect to $L_{50\%}$:

$$\ln(L_{50\%}) = \ln(SF) + \gamma_0 + \ln(d_{eff}) + (\gamma_d * Z_d) + (\gamma_t * t) + (\gamma_S * S) + (\gamma_d * \ln(d) * Z_d),$$

(23)

Where: γ are regression coefficients;

Parameterisation with respect to SR:

$$\ln(SR) = \beta_0 + (\beta_d * \ln(d_{eff})) + (\beta_d * Z_d) + (\beta_t * t) + (\beta_S * S) + (\beta_d * \ln(d) * Z_d),$$

(24)

Where: β are regression coefficients.

Equations (23) and (24) are substituted into the basic parameterised selectivity model (8), with random effects included in order to reflect the variation between hauls:

$$\ln(L_{50\%_i}) = \ln(L_{50\%}(x_i) + u_i \quad \text{and} \quad \ln(SR) = \ln(SR(x_i) + v_i; \quad \begin{bmatrix} u_i \\ v_i \end{bmatrix} \sim N(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \Sigma),$$

(25)

where: u_i and v_i are random effects for the i-th trawl.

Experimental data and statistical modelling for the assessment of operational selectivity.

The analytical approach was developed in accordance with the complex model (equation 2), in which the selectivity of the fishing gear is determined through the effective mesh opening $d_{eff}(x)$, defined as a function of design and operational parameters.

The selection process is described through the parameters $L_{50\%}$ – the length at which the retention probability is 50% – and SR – the selection range. In the empirical approach applied, these parameters are not estimated directly through a classical logistic function, but are derived indirectly through analysis of the observed size structure of the retained catch.

The programme script used represents a statistical implementation of this conceptual framework, its main purpose being to assess whether the variations in the size-frequency distribution of the retained catch can be explained by the design and the operational parameters.

Definition of the dependent variable

The analysis is structured at the level of the combination "haul × biological species × size class", the dependent variable being defined as the number of retained individuals:
Y_{isl} = number of retained individuals of species s in size class l in the i-th haul

Statistical model and stages of the analysis

In the first stage the empirical size-frequency distributions and their corresponding cumulative functions are calculated, from which the quantile indicators L_5, L_{25}, L_{50}, L_{75} and L_{95} are extracted.

In the second stage a generalized additive model (GAM) with a negative binomial (NB) distribution is applied for modelling the number of retained individuals. The general structure of the model is described by:

$$\log(\mu_{isl}) = \alpha + \text{Gear}_i + f_{\text{Gear}}(L_l) + \text{Year}_i + b_i + \log(N_i) \quad (26)$$

where: μ_{isl} is the expected number of retained individuals, α – a constant (intercept), Gear_i – the effect of the trawl, $f_{\text{Gear}}(L_l)$ is a nonlinear smooth function of length, specific to the gear type, $b_i$is a random effect at haul level (intended to model the variations not explained by the model), Year_i – the effect of the year, which tests whether there is a systematic difference in selectivity between the different years in which the experiments were carried out, and $\log(N_i)$ is the logarithm of the total catch and plays the role of a normalising term accounting for the intensity of the haul.

For the species *M. merlangus* a two-component (hurdle) model was applied, which divides the retention process into two parts: the probability of the presence of a catch (binomial component) and, where a catch is present, the number of retained individuals (negative binomial distribution). A random effect at haul level was included in both components.

Methodological justification of the applied model

The choice of the applied model (a generalized additive model with a negative binomial distribution) is determined by the need to describe the nonlinear character of selectivity by length/size class without a fixed functional form being specified in advance. The negative binomial distribution was used because of the presence of overdispersion in the count data (biological heterogeneity, operational differences, species-specific selectivity and the presence of many zero observations).

The inclusion of a random effect at haul level makes it possible to account for the unmeasured variability between the individual operations, which is essential for the correct interpretation of the results. In *M. merlangus*, the use of a two-component model is dictated by the presence of a considerable number of zero observations, which requires differentiated modelling of the process of occurrence of the catch.

Design parameters and limitations in the modelling

The design characteristics of the gears are strongly correlated with the factor $Gear$, for which reason their simultaneous inclusion in the main model would lead to multicollinearity and erroneous results for the estimated parameters. For this reason the factor $Gear$ is used in the main model as an aggregate indicator of the design profile, while the influence of the individual parameters is assessed through separate sensitivity models.

Relationship between L50 and L50%

The indicator L_{50}, derived from the cumulative distribution of the retained catch, is used as an empirical analogue of the theoretical parameter $L_{50\%}$. In the absence of data on the individuals that passed through the netting, this approach is considered an adequate

approximation of the selection profile, the interpretation remaining within the framework of operational selectivity.

Sensitivity analysis

The sensitivity analysis was implemented through the inclusion of interactions between length and operational variables by means of tensor smooth functions of the type $ti(L, X)$. For the design parameters, separate models were used without the inclusion of the factor Gear, in order to avoid collinearity.

Predictions and extraction of quantile estimates

The model predictions were generated over a dense grid of lengths (total length in cm within the range of the measured lengths) at fixed reference values of the operational variables and without the inclusion of the random effect. The values obtained were normalised to unit area, after which the quantile indicators were extracted from the cumulative distribution.

Assessment of uncertainty

Uncertainty was assessed through bootstrapping at haul level, which makes it possible to preserve the internal dependence of the observations and to obtain reliable confidence intervals for the model estimates.

Model comparison and diagnostic assessment

The comparison between the alternative model specifications is carried out through information criteria and assessment of goodness of fit, including AIC, BIC and, where applicable, a likelihood ratio test. The diagnostic assessment includes checking for overdispersion, analysis of the residuals, assessment of parameter stability and examination of the influence of individual hauls on the model predictions. This approach makes it possible to avoid overparameterisation and to select a model that combines statistical adequacy, biological interpretability and applicability to real fishing conditions.

RESULTS AND DISCUSSION

In *M. barbatus* (Figure 5.1) the size-frequency distribution is concentrated mainly in the interval 8–12 cm, with a modal class of around 10 cm, the differences between the three design variants of the trawl being negligible. In *M. merlangus* (Figure 5.2) the size distribution covers a wider range (8–18 cm), with a modal class of around 12 cm and a weakly expressed shift towards larger sizes in Trawl 3.

The comparative analysis shows that *M. merlangus* is characterised by greater size variability of the catch, whereas in *M. barbatus* the size structure is more compact. The established differences correspond to the biological features of the two species and indicate a different sensitivity to the selective characteristics of the trawl gear.

The results obtained show a manifestation of operational selectivity, expressed in the limited retention of the smallest individuals. The weak participation of the largest size classes in the catch is explained predominantly by the population structure of the species studied and not by the selective characteristics of the trawls used.

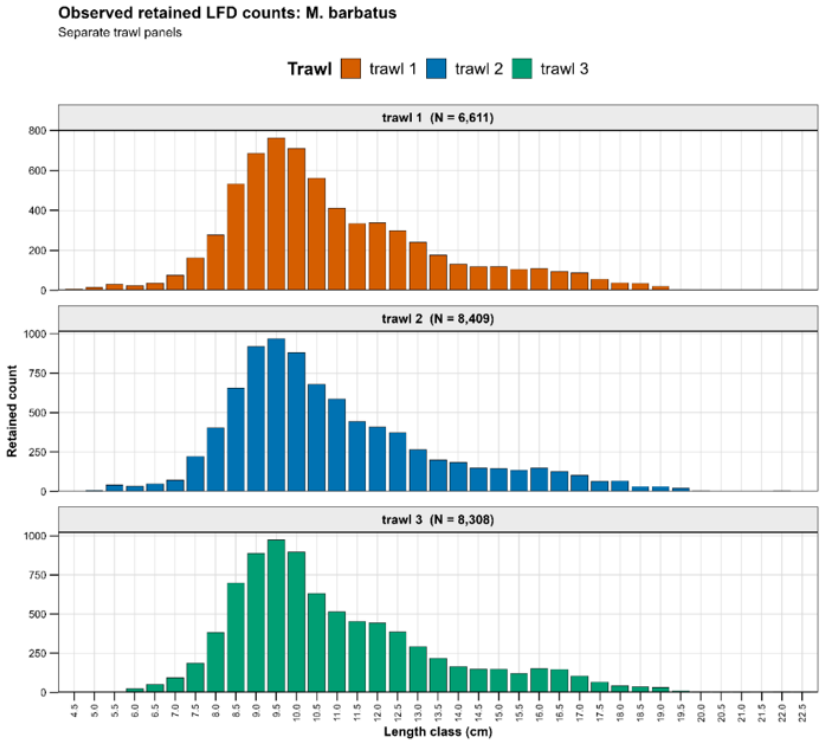


Figure 5.1. Observed size-frequency distributions in the retained catch of *M. barbatus* by trawl modification (Trawl 1, Trawl 2, Trawl 3) – separate panels by haul.

Statistical determination of the models and explained variation

The generalized additive models show a high degree of suitability for describing the size structure of the retained catch in the two species studied – *M. barbatus* and *M. merlangus*. Nevertheless, substantial differences are established between them with respect to the degree of explained variation and the complexity of the modelled selection process (Table 5.1).

Table 5.1. Comparative assessment of the statistical suitability of the single-component and the two-component (hurdle) generalized additive model for the two species studied.

Species	Model/ distribution	Total number of observations (n)	Total number of hauls (m)	AIC (Akaike information criterion)	Variation explained by the model (%)	Coefficient of determination Adj. R^2
M. barbatus	GAM (NB)/ (Negative Binomial)	6845	185	20112.85	**83.11**	0.8345

M. merlangus	Hurdle GAM (Binomial + NB)	3420	114	13034.67	**51.44**	0.5258

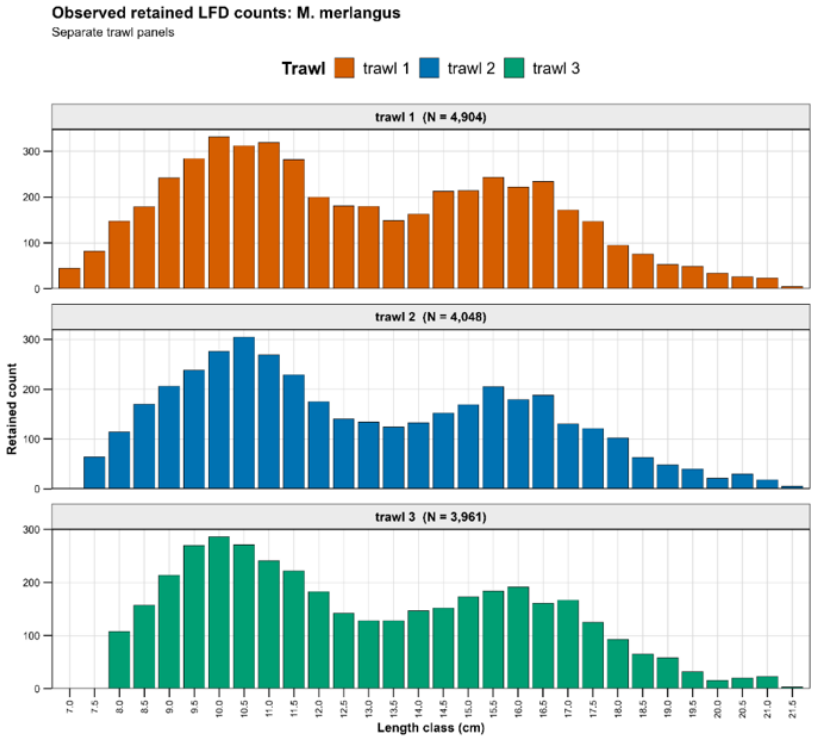


Figure 5. 2. Observed size-frequency distributions in the retained catch of *M. merlangus* by trawl modification (Trawl 1, Trawl 2, Trawl 3) – separate panels by haul.

The model for *M. barbatus* explains 83.11% of the variation in the size structure of the retained catch, which indicates very good statistical suitability. In *M. merlangus* the explained variation is lower because of the higher heterogeneity between hauls and the presence of zero observations, which justifies the use of a two-component (hurdle) model.

The modelled selection curves (Figure 5.3 and Figure 5.4) adequately describe the mean retention length and the selection range. In *M. barbatus* the curves for the three design variants practically overlap, which indicates a relatively stable selection process. In *M. merlangus* they are smoother and with a wider transition range, reflecting the joint influence of design, operational and behavioural factors.

The results confirm the statistical suitability of the models and allow a biologically justified assessment of operational selectivity under real trawl fishing conditions.

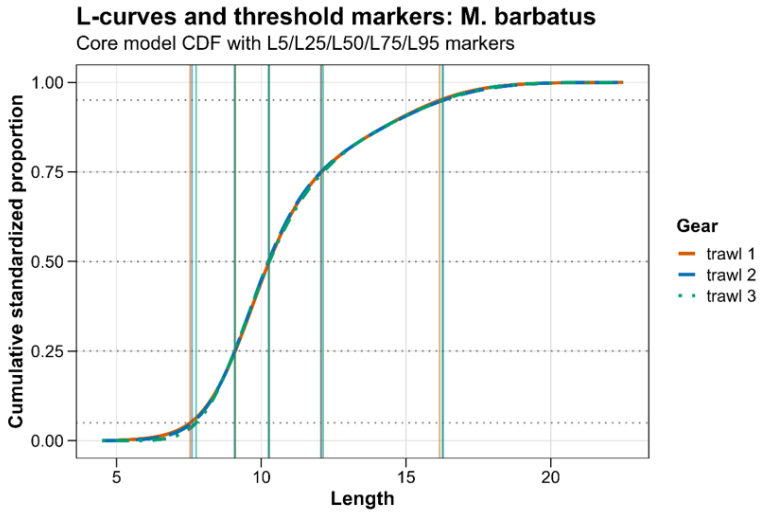


Figure 5.3. Cumulative selection curves with threshold values L_5, L_{25}, L_{50}, $L_{75}$and $L_{95}$for the three experimental trawls for *M. barbatus*

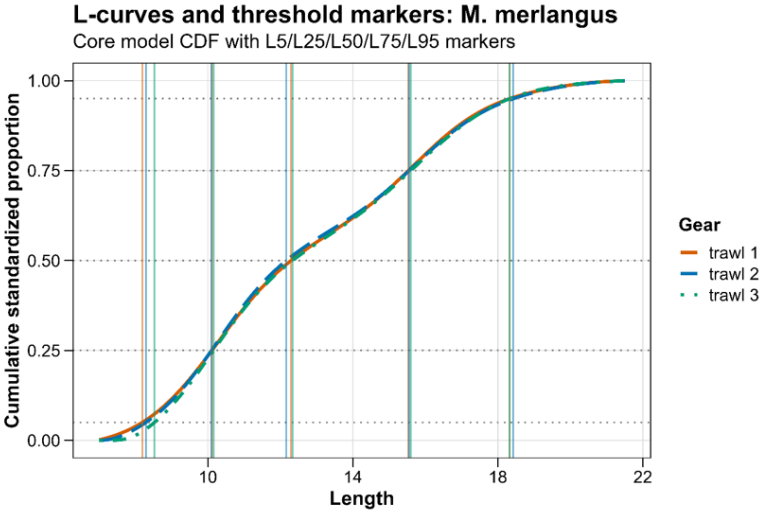


Figure 5.4. Cumulative selection curves with threshold values L_5, L_{25}, L_{50}, $L_{75}$and $L_{95}$for the three experimental trawls for *M. merlangus*

Statistical significance of the modelled effects

Parametric effects

The results of the analysis of the parametric effects (Figure 5.5 and Figure 5.6) show a species-specific influence of the design characteristics of the trawl on operational selectivity.

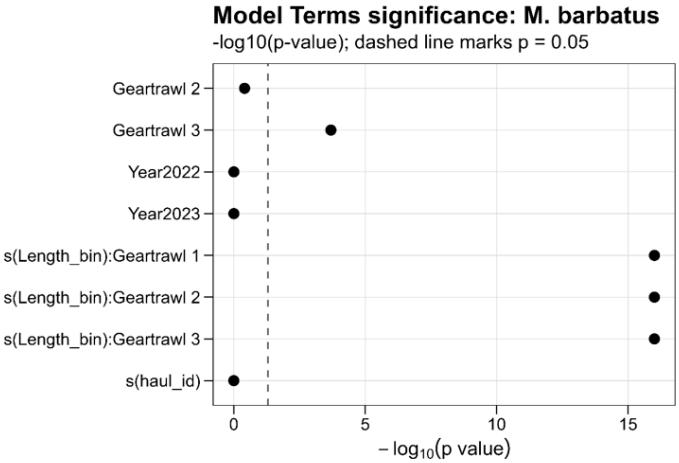


Figure 5.5. Statistical significance of the effects in the generalized additive model (GAM) describing the retained size structure in the catches of *M. barbatus*. The dashed vertical line denotes the threshold of statistical significance $p = 0{,}05$.

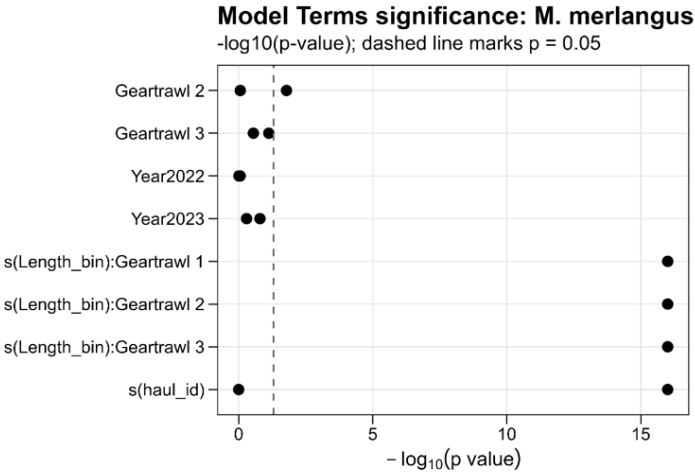


Figure 5.6. Statistical significance of the effects in the generalized additive model (GAM) describing the retained size structure in the catches of *M. merlangus*. The dashed vertical line denotes the threshold of statistical significance $p = 0{,}05$.

In *M. barbatus* a statistically significant effect was established only for Trawl 3, in which a reduction is observed in the expected number of retained individuals relative to the reference variant, which testifies to higher operational selectivity. No statistically significant influence of inter-annual variability was established.

In *M. merlangus* the design differences influence mainly the probability of retention of the individuals, while no statistically significant differences are established with respect to the intensity of the catch. Similarly, no substantial effect of inter-annual variability was recorded.

The analysis of the nonlinear effects (Table 5.3) shows that the length of the individuals is the main factor determining the operational selectivity of the trawl gear. In both species a strongly statistically significant nonlinear relationship was established between the size of the fish and the probability of their retention.

Table 5.3. Statistical significance of the nonlinear interactions ($ti(Length, X)$) and of the variation between hauls

Species	Model/ Component of the model	Effect	Probability p at significance level $\alpha = 0.05$	Statistical significance	Interpretation
M. barbatus	NB	s(Length):Gear	<0.001	Significant	Strongly pronounced nonlinear selectivity by length
M. barbatus	NB	s(haul_id)	1	Not significant	Absence of evidence of significant variation between hauls
M. merlangus	Presence	s(Length):Gear	<0.001	Significant	Strongly pronounced nonlinear relationship
M. merlangus	Presence	s(haul_id)	<0.001	Significant	Considerable effect of the variation between hauls (when the species is present)
M. merlangus	Positive count	s(Length):Gear	<0.001	Significant	Strong nonlinear effect of haul intensity
M. merlangus	Positive count	s(haul_id)	1	Not significant	Absence of variation between hauls when a catch is present

Substantial differences are observed with respect to the variation between the individual hauls. In *M. barbatus* it does not have a substantial influence on selectivity, whereas in *M. merlangus* it affects the probability of retention, which confirms the higher

sensitivity of the species to the towing conditions and justifies the application of the two-component (hurdle) model.

The results obtained confirm that operational selectivity is a species-specific process, being determined in *M. barbatus* predominantly by the design characteristics of the trawl, and in *Merlangius merlangus* by their interaction with the towing conditions.

Sensitivity analysis

The sensitivity analysis (Table 5.4) assesses the influence of the main operational factors on the operational selectivity of the trawl gear used. The results obtained show a clear distinction between the impact of the operational parameters on the total quantity of the retained catch and on the size-dependent selection process.

The main effects, described through the smooth functions $s(X)$, are not statistically significant for any of the variables analysed in the two species studied. This shows that factors such as towing duration, catch size and netting tension do not have a substantial influence on the total number of retained individuals.

In contrast, the interactions $ti(\text{Length}, X)$ do influence selectivity by length, i.e. the probability of retention of the individual size classes. The results obtained show that the sensitivity of the selection process to the operational factors is clearly species-specific.

Table 5.4. Influence of the operational factors on selectivity (sensitivity analysis)

Biological species	**Variable**	**Main effect ($s(X)$)**	**Interaction ($ti(L, X)$)**	**Probability p at significance level $\alpha = 0.05$**	**Interpretation**
M. barbatus	All	not significant	Not significant	>0.1	No demonstrated influence on selectivity
M. merlangus	Year	not significant	Weak	~0.07	Weak effect on the selection profile
M. merlangus	Catch quantity	not significant	Weak	~0.05	Weak (borderline) influence on selectivity
M. merlangus	Netting tension	not significant	Significant	0.026	Significant effect on selectivity

According to the results obtained, in *M. barbatus* operational selectivity represents a stable process which is practically unaffected by the operational factors analysed. In contrast, in *M. merlangus* the mechanical characteristics of towing, and in particular the netting tension, have a statistically significant influence on the selection process. This underlines the need, in assessing the selectivity of this species, for the main operational parameters of the fishing operation to be taken into account alongside the design characteristics of the trawl.

Size structure of the retained catch

The analysis of the size structure of the retained catch (Table 7) shows clearly expressed differences between the two species studied. In *M. barbatus* the median length is around 10 cm and the selection range is approximately 3 cm, which characterises a compact

size structure and relatively stable selectivity. In *M. merlangus* the median length is around 12 cm and the selection range reaches approximately 5.4 cm, which indicates a wider size distribution and higher variability of the selection process.

The results obtained (Table 5.5) confirm the more stable operational selectivity in *M. barbatus* and the more complex, more variable selection process in *M. merlangus*.

Table 5.5. Observed quantile characteristics of the retained catch

Biological species	***Trawl***	L_5 ***(cm)***	L_{25} ***(cm)***	L_{50} ***(cm)***	L_{75} ***(cm)***	***SR*** $(L_{75} - L_{25})$ ***(cm)***
M. barbatus	1	7.43	8.86	9.99	12	3.14
M. barbatus	2	7.50	8.84	9.98	11.9	3.06
M. barbatus	3	7.58	8.86	9.98	12	3.14
M. merlangus	1	7.90	9.87	12.1	15.3	5.43
M. merlangus	2	8.07	9.90	11.9	15.3	5.40
M. merlangus	3	8.28	9.92	12.1	15.4	5.48

Validation of the model estimates

The validation of the model estimates was carried out through comparison between the observed and the modelled values of the median length and of the main quantile characteristics of the size distribution.

The differences between the observed and the modelled values of L_{50} are below 0.3 cm for all combinations of species and trawl (Table 5.6, Figure 5.7), which indicates very high accuracy of the model estimates and good reproducibility of the central tendency of the size-frequency distributions.

Table 5.6. Comparison between observed and modelled values of L_{50}

Biological species	***Trawl***	***Observed*** L_{50} ***(cm)***	***Modelled*** L_{50} ***(cm)***	***Difference (cm)***
M. barbatus	1	9.99	10.3	0.29
M. barbatus	2	9.98	10.2	0.27
M. barbatus	3	9.98	10.3	0.3
M. merlangus	1	12.1	12.3	0.22
M. merlangus	2	11.9	12.2	0.23
M. merlangus	3	12.1	12.3	0.24

The graphical validation was carried out through comparison between the observed and the modelled quantile characteristics ($L_5, L_{25}, L_{50}, L_{75}$ and L_{95}) for each combination of biological species and design variant of the trawl (Figure 5.8).

The results show a very high degree of correspondence between the observed and the modelled values. The practical overlap of the quantile curves shows that the models used successfully reproduce not only the median length (L_{50}) but also the overall shape of the size distribution of the retained catch.

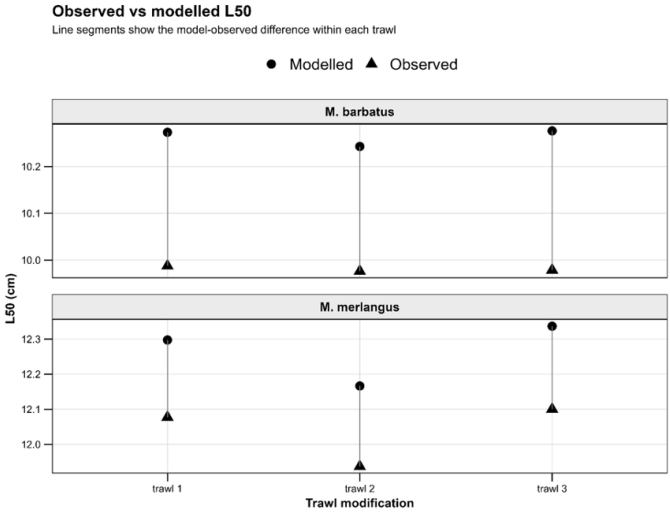


Figure 5.7. Comparison between the observed and the modelled values of L50 for the three experimental trawls in the two species studied. The segments show the difference between the modelled and the observed values of L_{50} for the three trawl types. The differences between the observed and the modelled values of L_{50} are below 0.3 cm for all combinations of species and trawl.

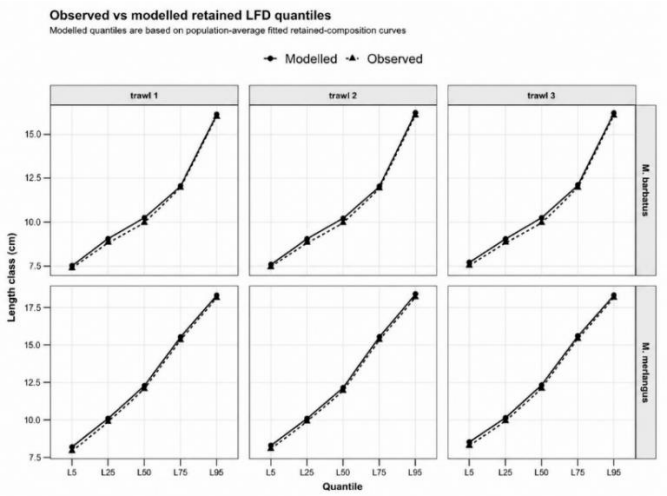


Figure 5.8. Observed and modelled quantile characteristics (L_5, L_{25}, L_{50}, L_{75} and L_{95}) for each combination of biological species and trawl modification.

Discussion

The results obtained show that the operational selectivity of conventional trawl gear has a clearly expressed species-specific character. Despite the similar fishing conditions, substantial differences are established between *M. barbatus* and *M. merlangus* in the size structure of the catch and in the mechanisms determining the probability of retention.

In *M. barbatus* operational selectivity is characterised by relative stability and is determined predominantly by the design characteristics of the codend and the morphological features of the species. In *M. merlangus* the selection process is more complex and is influenced both by the design characteristics of the trawl and by the operational conditions and the behavioural features of the species.

The established nonlinear relationship between the length of the individuals and the probability of their retention confirms that selectivity is a size-dependent process, determined by the interaction between the morphometric characteristics of the fish and the design parameters of the codend.

The validation of the models shows good correspondence between the observed and the predicted selectivity parameters, which confirms their applicability for the quantitative assessment of operational selectivity under real trawl fishing conditions.

The results obtained are consistent with contemporary scientific research and contribute new data on the operational selectivity of trawl gear in the Bulgarian Black Sea area, which can be used in the development of technical measures for the sustainable management of fish resources.

SCIENTIFICALLY JUSTIFIED RECOMMENDATIONS FOR IMPROVING OPERATIONAL SELECTIVITY AND THE SUSTAINABLE MANAGEMENT OF THE FISHERY FOR DEMERSAL AND NEAR-BOTTOM SPECIES IN THE BULGARIAN WATERS OF THE BLACK SEA

Interpretation of the results of the assessment of operational selectivity in the context of population dynamics

The assessment of operational selectivity is of essential importance for the sustainable management of fish resources, since it determines the extent to which sexually immature individuals participate in the catch. One of the main indicators of the biological effectiveness of selectivity is the ratio between the length of retention at 50% probability (L_{50}) and the length at attainment of sexual maturity (L_{m50}).

The comparison between the modelled values of L_{50} and the reference values for L_{m50} shows that, for all analysed variants of the trawl gear, L_{50} remains below the biological reference value in both species studied (Table 6.1). This means that a considerable part of the retained individuals had not attained sexual maturity at the moment of capture and that there is a real probability of fishing mortality being concentrated on age groups that do not yet participate effectively in the reproduction of the population.

Table 6.1 Comparison between the values reported in the literature for Lm_{50} and the estimated values for L_{50}

Biological species	Trawl	Reference value for Lm_{50} (cm)	Estimated / modelled value for L_{50} (cm)	Difference between the literature and the modelled value $L_{m50} - L_{50}$ (cm)

Biological species	Trawl	Reference value for Lm_{50} (cm)	Estimated / modelled value for L_{50} (cm)	Difference between the literature and the modelled value $L_{m50} - L_{50}$ (cm)
M. barbatus	Trawl 1	10.9	10.2	-0.7
M. barbatus	Trawl 2	10.9	10.3	-0.6
M. barbatus	Trawl 3	10.9	10.3	-0.6
M. merlangus	Trawl 1	13.9	12.3	-1.6
M. merlangus	Trawl 2	13.9	12.2	-1.7
M. merlangus	Trawl 3	13.9	12.3	-1.6

The results obtained are also confirmed by the analysis of the relative share of individuals with a total length below L_{m50} in the structure of the retained catch. Both the observed and the modelled distributions show consistently high values of this indicator (Figure 6.2), which testifies to insufficient selectivity of the trawl constructions used with respect to sexually immature individuals.

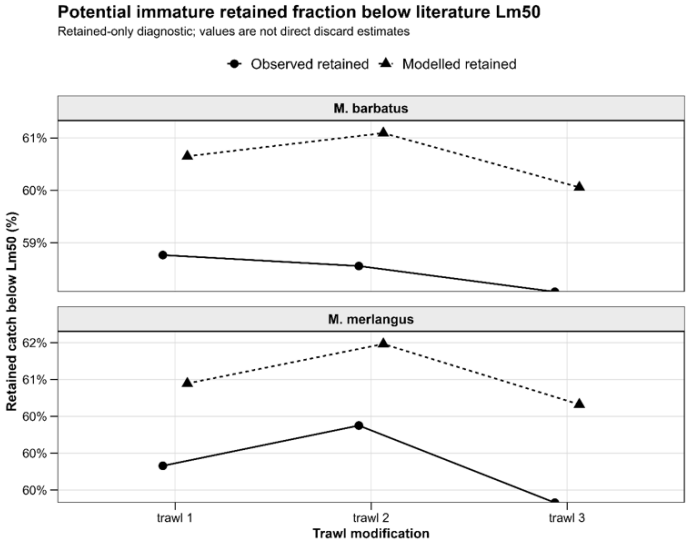


Figure 6.2. Comparison between the observed and the modelled share of individuals retained in the composition of the catch with a total length below the reference L_{m50}. A diagnostic indicator of the retained catch only; the values are not direct estimates of discards.

In *M. barbatus* the share of retained individuals below L_{m50} varies between 58.1% and 58.8% according to the observed data and between 60.1% and 61.1% according to the

model estimates, depending on the codend construction used (Table 6.2, Figure 6.3). The highest values were established for Trawl 2, in which the modelled share of retained sexually immature individuals reaches approximately 61.1%. Although the differences between the individual variants are comparatively small, all the constructions studied show a high probability of retaining individuals that have not attained sexual maturity.

In *M. merlangus* a similar but even more unfavourable tendency is observed. The share of retained individuals below L_{m50} varies between 59.3% and 60.4% according to the observed data and between 60.7% and 62.0% according to the model estimates (Table 6.2), which corresponds to the results of analogous studies in the Black Sea (Moussa et al., 2026). Notwithstanding the use of a construction with higher structural stability of the netting panel (PE + Dyneema), the share of retained sexually immature individuals remains high. The established high values of retention of individuals below L_{m50} should be regarded not only as an indicator of intensive fishing pressure on the early age groups, but also as an indicator of potentially high levels of discards and the associated additional fishing mortality. In trawl fisheries a considerable part of the catch, formed by undersized or economically unwanted specimens, is returned to the marine environment after sorting on board. Notwithstanding that these individuals do not participate in the realised catch, in most cases their survival is low because of mechanical injury, physiological stress, compression, hypoxia and disturbances of osmoregulation occurring during towing and handling of the catch (Davis, 2002; Suuronen, 2005; Broadhurst et al., 2006; Uhlmann et al., 2006).

Table 6.2 Observed and modelled share (%) of individuals retained in the catch with a total length below the length at 50% sexual maturity established in the literature (L_{m50}) for *M. barbatus* and *Merlangius merlangus* for the different modifications of the trawl gear studied.

Biological species	**Trawl**	**Observed share of individuals retained in the catch below Lm_{50} (%)**	**Modelled share of individuals retained in the catch below Lm_{50} (%)**
M. barbatus	Trawl 1	58.8	60.7
M. barbatus	Trawl 2	58.6	61.1
M. barbatus	Trawl 3	58.1	60.1
M. merlangus	Trawl 1	59.8	61
M. merlangus	Trawl 2	60.4	62
M. merlangus	Trawl 3	59.3	60.4

For this reason discards are regarded as a substantial component of total fishing mortality (Forrest et al., 2001; ICES, 2005; Kelleher, 2005; Agnew et al., 2009) and as one of the most important indicators of insufficient operational selectivity. With a high share of retained sexually immature individuals, the probability of subsequent discarding is considerable, particularly for size classes of low commercial value. This leads to a doubly negative impact on the populations – an increase in fishing mortality on individuals that have not participated in reproduction, and a limitation of the future recruitment of the stocks.

The results obtained show that the assessment of operational selectivity should be regarded not only as a characteristic of the size structure of the catch, but as an integral

indicator of potential fishing mortality, of the impact on stock recruitment and of the effectiveness of the measures for sustainable management.

The observed relationships should also be interpreted in the context of the biological features of the two species. *M. barbatus* is characterised by relatively fast growth, early attainment of sexual maturity and a comparatively short life cycle (Froese, 2005), which to a certain extent increases the resilience of the population to moderate fishing pressure on the younger age groups. Notwithstanding this, the prolonged removal of a large number of sexually immature individuals may lead to a reduction of the effective reproductive biomass and a limitation of recruitment (Daskalov, 2002), particularly under unfavourable ecological conditions.

In *M. merlangus* the potential impact on population dynamics is even more substantial. The species attains sexual maturity at larger sizes and is characterised by a wider size range in the structure of the catch (Volodin, 1996; İşmen, 2002; Bilgin et al., 2012). This result acquires particular significance in view of the assessments that the stock of the species in the Black Sea is in a state of overexploitation (FAO, 2023).

Analysis of the regulatory framework in force and the need to update the technical measures

According to Annex No. 2 to Art. 38, para. 1 of the Fisheries and Aquaculture Act (Fisheries and Aquaculture Act. Promulgated, State Gazette No. 41 of 24 April 2001), the minimum permissible catch size is defined as 8 cm both for Black Sea whiting (*M. merlangus*) and for red mullet (*M. barbatus*).

The comparison between the minimum permissible catch sizes defined by the regulations and the values of L_{m50} established in the literature shows the presence of a substantial discrepancy between the biological characteristics of the species and the regulatory thresholds in force.

For *M. barbatus* the values published in the scientific literature for L_{m50} are in the range 10.5–11.5 cm, and for *M. merlangus* in the range 13–15 cm, depending on the method used and the population studied. This means that the regulatory framework in force permits the legal retention and landing of a considerable share of sexually immature individuals and juvenile fish, which have probably not participated even once in the reproductive cycle of the stock.

The results obtained show that the modelled values of L_{50} remain below the length at attainment of sexual maturity L_{m50} in both species studied. This shows that a considerable part of the retained individuals are caught before participating in reproduction, which limits the reproductive potential of the stocks and calls into question the effectiveness of the minimum permissible sizes as a stand-alone management instrument (Prodanov, 1997; Daskalov and Rätz, 2011).

Insufficient size selectivity creates the preconditions for an increase in bycatch and discards, which represent a substantial component of total fishing mortality. This underlines the need to combine the regulatory measures with technological solutions for improving the operational selectivity of fishing gear.

The results show that operational selectivity is determined by the interaction between the design characteristics of the trawl, the size structure of the populations and the conditions of operation. In *M. barbatus* selectivity is relatively stable and is influenced predominantly by the design characteristics of the gear, which is consistent with the results of Kalaycı and Yeşilçiçek (2012), Raykov et al. (2021) and Moussa et al. (2026). In *M. merlangus* a higher sensitivity to the operational conditions is observed, which corresponds to the results reported by Zengin et al. (2019) and Moussa et al. (2026).

From the point of view of population dynamics, the capture of sexually immature individuals increases the risk of a reduction in recruitment and of disturbance of the size and age structure of the stocks, which is characteristic of intensively exploited fish populations (Hutchings and Myers, 1994; Gislason and Rice, 1998; Pauly et al., 1998; Gascuel et al., 2007; Branch et al., 2010). The results obtained confirm the need to apply biologically justified technical measures for improving the selectivity of trawl gear as an element of the sustainable management of fish resources in the Black Sea.

Scientifically justified technical recommendations for improving operational selectivity

The results of the present study, considered in the context of the theoretical framework, the statistical modelling of operational selectivity and the analysis of the effects on population dynamics, show the need to apply a scientifically justified approach in determining the technical characteristics of the trawl gear used for catching demersal and near-bottom species in the Bulgarian waters of the Black Sea.

The analysis of operational selectivity shows that the conventional trawl constructions studied do not provide a sufficiently effective limitation of the retention of sexually immature individuals of *M. barbatus* and *M. merlangus*. Notwithstanding the differences in codend construction and in the netting materials used, in all configurations analysed the estimated values of L_{50} remain below the values of L_{m50} established in the literature, while the share of retained individuals below L_{m50} exceeds 58–60% of the total composition of the catch.

The results obtained show that limiting the fishing pressure on the young age groups cannot be achieved solely through the setting of minimum catch sizes. A complex approach is required, based on improving the operational selectivity of fishing gear, which would ensure the release of undersized individuals already during towing.

Improving selectivity has not only a biological but also a technological and economic effect, since it reduces unwanted catch and discards, shortens sorting time, improves the quality of the realised catch and increases the efficiency of fishing operations.

The results show that operational selectivity is the result of the interaction between the design characteristics of the trawl gear, the size structure of the populations and the conditions of operation. This requires that, in developing technical measures, account be taken not only of the nominal mesh size but also of the actual behaviour of the trawl gear in operation.

On the basis of the results obtained, scientifically justified recommendations have been formulated for optimising the design and operational characteristics of the trawl gear used in the capture of *M. barbatus* and *M. merlangus* in the Black Sea (Table 6.4).

Table 6.4 Recommended design characteristics of trawl gear for catching *M. barbatus* and *M. merlangus* and expected effect on operational selectivity.

Design element	**Existing practice**	**Scientifically justified recommendation**	**Expected effect on selectivity L_{50}**	**Expected share of retained individuals below L_{m50}**
Codend mesh size	32–36 mm	≥ 40 mm	Increase of L_{50} to (~11–12 cm) for *M. barbatus* and ~13–14 cm for *M. merlangus*	Reduction of the expected share to ~40–50%

Mesh geometry	Diamond	Square	Stabilisation of the selection profile	Additional reduction by ~5–10%
Codend material	PA; PE + Dyneema	Materials with low deformation and high dimensional stability	Limitation of the variability of L_{50}	Reduction of the variability of the size structure in retention
Codend construction	Conventional	Selective panels and "escape" windows	Increase of the probability of release	Reduction of the expected share to below ~35–45%
Protective outer cover of the trawl (to prevent mechanical damage to the codend)	Full covering of the trawl	Limited covering of the trawl	Maintenance of the effective mesh opening	Partial reduction of the retention of undersized and juvenile fish
Codend length	Conventional	Shortened and structurally stabilised	Limitation of the deformation of the netting panel and increase of the stability of the selection process	Reduction of the variability in the retention of small size classes
Codend loading	Uncontrolled maximum loading (high variation)	Controlled maximum loading	Maintenance of a more stable effective mesh opening in operation	Limitation of retention at high catch density

The values presented are of an analytical and predictive character and are based on a comparative interpretation of the results of the present study, published literature data on the selectivity of trawl gear in the Black Sea and the theoretical relationships between mesh size, the selection threshold L_{50} and the probability of retention of individuals below L_{m50}.

From a management perspective, the results show the need for a transition from a static to a functional approach in the regulation of fishing gear selectivity. The regulatory framework in force is focused mainly on the nominal mesh size and the minimum permissible catch sizes, without accounting for the actual behaviour of the netting panel in operation and its influence on the probability of retention of immature individuals.

On the basis of the results obtained, the present dissertation recommends the introduction of an adaptive system for the regulation of selectivity, based on:

- the biological reference points of the exploited species;
- the operational characteristics of the fishing gear;
- the actual conditions of operation;
- quantitative indicators of the retention of immature individuals;
- assessment of the selection threshold L_{50} and the probability of retention of individuals below L_{m50}

Such an approach would allow a more precise regulation of the fishing pressure on the different size classes and age groups and would create a more reliable basis for the sustainable management of the stocks of *M. barbatus* and *M. merlangus* in the Black Sea.

Assessment of the potential effect of different management scenarios

On the basis of the results obtained, three main management scenarios have been considered, reflecting different levels of technical and regulatory intervention.

Scenario 1 – Retention of the existing regime

The first scenario assumes the retention of the current characteristics of the trawl gear, the existing codend mesh sizes and the minimum permissible catch sizes in force, regulated in the Fisheries and Aquaculture Act. Under this regime operational selectivity remains practically unchanged, and the values of L_{50} continue to lie below the biologically justified values of L_{m50} in both species studied.

The results obtained show that under such a scenario a considerable part of the retained individuals will continue to be formed by biologically immature specimens (Table 6.6). This means that fishing mortality remains concentrated on the young age groups, before the individuals have participated effectively in the reproductive process. In the long term, such a structure of exploitation creates the preconditions for a progressive decrease in the mean age and size in the population, a reduction of age diversity and a decrease of the effective reproductive biomass.

Table 6.6. Predicted effects under retention of the existing operational regimes.

Indicator	***M. barbatus***	***M. merlangus***
Expected L_{50}	~10.2–10.3 cm	~12.2–12.3 cm
Values reported in the literature for L_{m50}	~10.5–11.5 cm	~13–15 cm
Expected share of retained individuals below L_{m50}	58–61%	60–62%
Tendencies in the size structure	Decrease of the mean length of the individuals in the population and reduction of the reproductive potential	Strongly pronounced decrease of the mean length of the individuals in the population and reduction of the reproductive potential

This effect is particularly problematic in *M. merlangus*, in which sexual maturation occurs at larger sizes, while the analysis of operational selectivity shows a higher probability of retention of individuals below L_{m50}. Under such a regime of exploitation there is a risk of so-called "size truncation" – a decrease in the mean length in the size structure of the population, in which the relative share of the older and larger individuals, characterised by a higher reproductive potential, gradually declines.

Scenario 2 – Partial improvement of selectivity

This scenario considers the introduction of limited technical measures for improving selectivity, including an increase of the codend mesh size to ≥ 40 mm, the use of more stable netting constructions and partial optimisation of the codend. If such measures are undertaken, a moderate increase in the values of L_{50} may be expected and, accordingly, a reduction of the expected share of retained individuals with a length below L_{m50} (Table 6.7). The improvement of selectivity in this case is based mainly on increasing the probability of release of the small size classes during their passage through the codend.

Table 6.7. Predicted effects under partial improvement of selectivity.

Indicator	*M. barbatus*	*M. merlangus*
Expected L_{50}	~10.8–11.2 cm	~13.0–13.5 cm
Expected share of retained individuals below L_{m50}	45–52%	48–55%
Expected reduction of juvenile fish	~10–15%	~8–12%
Risk of recruitment overexploitation	Moderate	Moderate to high
Tendencies in the reproductive potential of the population	Partial stabilisation	Improvement

With respect to the state of the population, such a change would lead to a partial recovery of the size structure of the stocks and to an increase of the probability that individuals participate at least once in reproduction before being included in fishing mortality. The expected effect, however, will probably remain limited if the actual operational conditions influencing the behaviour of the netting panel during towing are not also taken into account.

Scenario 3 – Complex selective approach

The third scenario considered (Table 6.8) includes the combined application of technical and management measures aimed simultaneously at limiting the retention of immature individuals and improving the age and size structure of the stocks. The approach considered includes:

- an increase of the codend mesh size;
- the use of netting panels with square mesh geometry;
- control of the codend loading;
- control of the towing duration;
- the application of selective "escape" windows;
- limitation of the elements of the outer cover of the trawl;
- updating of the minimum permissible catch sizes in accordance with the biological reference points L_{m50}.

This scenario shows the highest potential for improving selectivity and reducing the fishing pressure on the immature age groups. The combined application of design and regulatory measures would lead to a considerable increase of the probability of release of the small size classes already during the fishing operation and, accordingly, to a reduction of the pressure on the juvenile fish.

Under such an approach, a gradual increase of the mean size and age in the structure of the stocks, a stabilisation of recruitment and an increase of the effective biomass may be expected. The improvement of the age structure is of particularly important significance for the sustainable development of the populations, since the older and larger individuals are usually characterised by higher individual fecundity and a greater contribution to the successful recruitment of the stocks.

Table 6.8. Predicted effects under a complex selective approach.

Indicator	*M. barbatus*	*M. merlangus*

Expected L_{50}	~11.5–12.0 cm	~13.8–14.5 cm
Expected share of retained individuals below L_{m50}	30–40%	35–45%
Expected reduction of juvenile fish	~25–35%	~20–30%
Risk of recruitment overexploitation	Positive	Considerable improvement
Tendencies in the reproductive potential of the population	Stabilisation	Recovery of the age structure

6.5. Conclusions

1. The results of the study carried out show that the operational selectivity of the conventional gear used for catching *M. barbatus* and *M. merlangus* in the Bulgarian waters of the Black Sea is insufficient with respect to limiting the retention of sexually immature individuals. In both species studied the estimated values of L_{50} remain below the values of L_{m50} established in the literature, which shows that a considerable part of the retained specimens had not attained sexual maturity at the moment of capture.

2. The comparative analysis between the observed and the modelled selectivity values shows a consistently high share of individuals below L_{m50} in the composition of the catch. For *M. barbatus* this share varies approximately between 58–61%, and for *M. merlangus* between 60–62%, irrespective of the codend modifications considered. The results obtained confirm that, with the existing design characteristics of the gear, fishing mortality is concentrated to a considerable extent on the early age groups.

3. The established values of operational selectivity should be interpreted not only as an indicator of the exploitation pressure on stock recruitment, but also as an indicator of potentially high levels of discards. The considerable probability of retention of small size classes implies the formation of a substantial quantity of unwanted catch, which is subsequently subject to sorting and potential discarding. This increases total fishing mortality and leads to additional fishing pressure on the populations, notwithstanding that some of these individuals do not formally participate in the realised catch.

4. The analysis also shows that the minimum permissible catch sizes laid down in the legislative framework in force do not correspond to the biological reference values for the attainment of sexual maturity. The minimum permissible size of 8 cm, both for *M. barbatus* and for *M. merlangus*, remains substantially below the values of L_{50} established in the literature, which means that the regulatory system in force permits the legal retention and landing of a considerable share of immature individuals. As a result, the minimum permissible sizes do not effectively fulfil their function as a mechanism for protecting the reproductive potential of the stocks.

5. The results obtained show that operational selectivity represents a complex result of the interaction between the design characteristics of the trawl gear, the mechanical properties of the materials used, the size structure of the population and the conditions of operation. Although operational parameters such as codend loading and towing duration influence the selection process, the results show that the design characteristics of the codend are of leading importance for the probability of retention of small size classes.

6. In *M. barbatus* a relatively stable selection profile is established under the different operational conditions, which suggests a stronger influence of the morphological features of the species and of the codend construction. In *M. merlangus* a higher sensitivity to changes in the conditions of operation is observed, which is probably related to the wider size range of the catch and to the features of the spatial distribution of the age groups.

7. The results of the analysis confirm the need to introduce scientifically justified technical measures for improving the selectivity of trawl gear. The highest potential for limiting the retention of immature individuals is shown by measures such as:

- an increase of the codend mesh size to ≥ 40 mm;
- the use of netting panels with square mesh geometry in the codend;
- the application of "escape" windows;
- limitation of the deformation of the netting panel;
- control of the codend loading;
- the use of materials with higher dimensional stability and lower deformation.

The testing of the different management scenarios shows that retaining the present regimes of exploitation would lead to continuing pressure on the young age groups and to a gradual disturbance of the size and age structure of the stocks. Partial improvement of selectivity would have a limited positive effect, but only the complex approach, combining technical and regulatory measures, shows the potential for a real reduction of the pressure on the small size classes (juvenile and undersized fish) and for stabilising the reproductive potential of the populations.

8. In the long term, the improvement of operational selectivity should be regarded not merely as a technical measure for optimising the catch, but as a key instrument for limiting discards, reducing fishing mortality on the immature age groups and ensuring the sustainable management of the stocks of demersal and benthic species in the Black Sea.

SUMMARISED RESULTS AND CONCLUSIONS

1. A substantial gap has been established in the scientific underpinning and the practical application of the concept of fishing gear selectivity in the Bulgarian Black Sea fishery, which hampers the sustainable management of fish resources.

2. An integrated methodological framework has been developed for the assessment of the operational selectivity of conventional trawl fishing gear, combining the design characteristics of the gear, the biological features of the species, the operational parameters and contemporary statistical models.

3. The applicability of generalized additive models (GAM/GAMM) has been demonstrated for the quantitative assessment of operational selectivity and for modelling the interaction between design, biological and operational factors.

4. It has been established that operational selectivity has a clearly expressed species-specific character. In *M. barbatus* it is determined predominantly by the design characteristics of the codend, whereas in *M. merlangus* the operational conditions also have a substantial influence.

5. It has been established that, with the trawl constructions studied, the values of L_{50} remain below the length at attainment of sexual maturity in both species, which indicates a risk of capturing sexually immature individuals and an unfavourable impact on the reproduction of the stocks.

6. It has been demonstrated that operational selectivity is a reliable indicator for assessing the sustainability of the fishery and can be used in assessing bycatch, discards and the impact of fishing on the exploited populations.

7. The results obtained justify the need to improve the technical measures for selectivity and to apply a scientifically justified approach in the management of the fishery, in accordance with the principles of the Common Fisheries Policy of the European Union.

8. The methodology developed creates a basis for building a national system for the monitoring and assessment of fishing gear selectivity and can support scientific advice and the sustainable management of fish resources in the Black Sea.

CONTRIBUTIONS OF THE DISSERTATION

SCIENTIFIC CONTRIBUTIONS

SC1. For the first time for the Bulgarian waters of the Black Sea, a complex analysis has been carried out of the operational selectivity of conventional trawl gear for catching *M. barbatus* and *M. merlangus*, including an assessment of the relationship between the selectivity of the fishing gear, the size structure of the catch, discards and the biological reference points of the exploited populations. It has been established that the observed and modelled values of L_{50} for the variants of conventional trawl gear used remain below the values of L_{m50} established in the literature, which indicates the presence of considerable fishing pressure on the sexually immature individuals and a risk of disturbance of the processes of stock recruitment.

SCIENTIFIC AND APPLIED CONTRIBUTIONS

SAC1. An applicable methodology has been developed for the assessment of the operational selectivity of trawl fishing gear under real conditions of operation, which can be used both in scientific research and in the practice of fisheries management. An analytical approach has been developed for the assessment of the effective mesh opening (d_{eff}), based on the inclusion of design and operational parameters related to the real conditions of towing.

SAC2. Science-based recommendations have been formulated for optimising the design characteristics of trawl gear for catching demersal and near-bottom species in the Black Sea, aimed at limiting the retention of sexually immature individuals and reducing discards.

SAC3. Specific technical and management measures have been proposed for improving the selectivity of trawl gear, including an increase of the codend mesh size, the use of panels with square mesh geometry, the application of selective escape windows and optimisation of the codend construction.

SAC4. Analytical and predictive management scenarios have been developed for assessing the effect of different selectivity regimes on the size and age structure of the stocks of *M. barbatus* and *M. merlangus*, including an assessment of the potential influence on the retention of juvenile fish, discard mortality and the pressure on recruitment.

SAC5. The results obtained provide a scientific basis for updating the regulatory framework related to the minimum permissible catch sizes and the technical characteristics of the fishing gear used in the Bulgarian waters of the Black Sea.

LIST OF ARTICLES RELATED TO THE DISSERTATION LIST OF PUBLICATIONS ON THE DISSERTATION

A1. RAYKOV, V., RAEV, Y., Petrov, K., & Nikolov, G. (2021). TRAWL SELECTIVITY OF FISHING GEARS TARGETING RED MULLET (Mullus barbatus L.) IN BULGARIAN MARINE ZONE. *Journal of Environmental Protection and Ecology, 22(1), 143-153. Q4 – 12 pts.*

Journal Indexed In: Journal of Environmental Protection and Ecology is indexed in Scopus with SJR = 0.147 (2024) and classified in Q4 quartile across environmental science categories

A2. Alexandrova, A., Raev, Y., Dimitrov, D., Chipev, N., Tsvetanova, E., Georgieva, A., & Raykov, V. (2022). Comparative study on the oxidative stress of commercially important fish species from localities with different ecological conditions along the Bulgarian Black Sea coast. *BioRisk, 17, 117-126. Q3 – 15 pts.*

Journal Indexed In: BioRisk is indexed in Scopus with SJR = 0.268 (2024) and classified in Q3 quartile in ecology and biodiversity sciences.

A3. Alexandrova, A. V., Chipev, N. H., Raev, Y. R., Tsvetanova, E. R., Georgieva, A. P., & Raykov, V. S. (2021). Is the Marine Environment of the Black Sea Stressful for Organisms: A Pilot Assessment of Oxidative Stress in Bulgarian Coastal Fish Species. *Ecologia Balkanica. Q4 – 12 pts.*

Journal Indexed In: Ecologia Balkanica is indexed in Scopus with SJR ≈ 0.19 and classified in Q4 quartile in ecology.

ABSTRACT

This dissertation investigates the operational selectivity of conventional bottom trawl fishing gear used for harvesting two commercially important demersal fish species in the Bulgarian Black Sea waters - red mullet (*Mullus barbatus* Linnaeus, 1758) and whiting (*Merlangius merlangus* Linnaeus, 1758). Improving fishing gear selectivity is one of the principal approaches for reducing bycatch and discards and for supporting the sustainable exploitation of marine living resources within the framework of the European Union Common Fisheries Policy and the ecosystem approach to fisheries management.

The study addresses a significant scientific and practical gap related to the limited experimental information on the selectivity of trawl codends used in the Bulgarian Black Sea fishery. The research aims to evaluate the operational selectivity of conventional trawl gear under commercial fishing conditions and to identify the influence of codend design, mesh size, netting material, and operational parameters on the retention probability of different size classes of the target species.

Experimental data were collected during commercial fishing operations carried out between 2021 and 2023 on the Bulgarian continental shelf of the Black Sea. Three conventional trawl configurations differing in codend construction, mesh size, and netting material were investigated. Biological samples of *M. barbatus* and *M. merlangus* were collected, and individual total length and body weight were recorded. Operational variables,

including towing speed, towing duration, catch weight, fishing depth, and codend characteristics, were documented for each haul.

The analytical framework combines a mechanistic concept of codend selectivity with advanced statistical modelling. Generalized Additive Models (GAM) and Generalized Additive Mixed Models (GAMM) with negative binomial and hurdle distributions were applied to quantify operational selectivity under real fishing conditions. The modelling approach incorporates both engineering characteristics of the fishing gear and operational variables, allowing estimation of size-dependent retention patterns, selectivity curves, median retention length (L_{50}), and selection range (SR).

The results demonstrate clear species-specific differences in operational selectivity. For *M. barbatus*, selectivity proved to be relatively stable and primarily determined by codend design, while operational variables had only limited influence. In contrast, *M. merlangus* exhibited considerably greater variability, with operational factors such as net tension contributing significantly to the selectivity process. The applied models successfully described the nonlinear relationship between fish length and retention probability, explaining approximately 83% of the variation for *M. barbatus* and over 51% for *M. merlangus*.

Comparison between the estimated L_{50} values and published lengths at first sexual maturity (L_{m50}) revealed that, for all investigated trawl configurations, median retention lengths remained below the biological maturity threshold for both species. Consequently, a substantial proportion of retained individuals had not yet reached sexual maturity, indicating that the existing trawl configurations provide insufficient protection for juvenile fish and may negatively affect stock recruitment and long-term sustainability.

The study further demonstrates that operational selectivity should be interpreted as an integrated characteristic resulting from the interaction between fishing gear design, fish population size structure, and fishing operation conditions, rather than solely as a function of nominal mesh size.

Based on the experimental findings, scientifically justified recommendations are proposed for improving trawl codend design through increased mesh size, improved netting geometry, optimized material properties, and adaptive technical measures aimed at reducing juvenile retention and unwanted catches. The dissertation also highlights the need to integrate biological reference points into fisheries management and suggests that operational selectivity should become a key indicator in future monitoring and assessment programmes.

The developed methodological framework provides a reliable scientific basis for evaluating trawl selectivity under commercial fishing conditions and can support future technical regulations, fisheries management strategies, and sustainable exploitation of marine living resources in the Bulgarian Black Sea.