Bachelor of Science in Environmental Sciences

Bachelor thesis

Aged and children first! Challenges in the development of a new selectivity concept in trawl fisheries

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Rostock, September 2015

Abstract

The selectivity properties of demersal trawls allow small fish to escape from catch, whereas medium sized and large individuals are retained in the gear. Recent studies demonstrate that large fish, normally targeted in commercial fisheries, have the highest and most stable reproduction rates. Therefore, the offspring production by larger fish can be essential for the sustainability of fishing stocks. These new findings in reproductive fish biology are strong reasons to reduce the fishing pressure on large fish. To achieve this, a new selectivity concept was developed for trawls. This concept enables, beyond small fish, also large fish to escape during towing. It is based on combining two well-known selectivity devices - a codend made of selective netting and a steel grid mounted ahead of the codend - to produce a sequential selection system in the experimental gear. With this new concept it is expected to obtain an innovative bell-shaped selection curve, which illustrates the fact that small and very large fish can escape while medium sized fish are caught. The new concept was tested successfully using the Baltic Sea cod (*Gadus morhua*) directed trawl fishery as case of study. Based on this, different setups of the grid and the escapement opening were tested to analyze their influence on the overall selectivity. The results show that it is possible to obtain a completely different exploitation pattern compared to traditional trawl selectivity and that the distribution of length classes in the catch can be controlled using different gear setups.

Keywords

Demersal trawl, cod, bellshape, Baltic Sea, size selection, exploitation pattern

Content

1. Introduction ... 1
   1.1 Demersal trawl fisheries ... 1
   1.2 Size selection in trawl gears ... 3
   1.3 New hypothesis for better exploitation patterns ... 6
   1.4 An attempt to achieve alternative harvesting in trawl fisheries through fishing technology .. 7
2. Material and Methods ... 10
   2.1 Gear description ... 10
   2.2 Model for describing selection curves ... 12
   2.3 Model selection and Inference ... 14
   2.4 Data collection ... 16
   2.5 Underwater observation ... 18
3. Results ... 20
   3.1 Gear setups and operational information ... 20
   3.2 Description of the catch ... 23
   3.3 Model selection ... 23
   3.4 Comparison of setups ... 25
   3.5 Underwater video ... 35
4. Discussion ... 38
   4.1 New exploitation pattern ... 38
   4.2 The grid ... 39
   4.3 The codend ... 41
   4.4 Fish behavior ... 42
   4.5 Conclusion ... 44

References ... 45

Acknowledgements ... 49

Appendix ... II

List of Abbreviations ... II

Technical drawing ... III

Pictures ... IV

Selbstständigkeitserklärung ... VI

1. Introduction

1.1 Demersal trawl fisheries

The demand of fish has never been as large as it is nowadays. Not only the world population is growing steadily but also the request per capita is increasing from 9.9 kg in the 1960s to 19.2 kg in 2012 (FAO, 2014). To satisfy this demand, about 65 million tonnes of marine fish are captured annually (FAO a, 2014), of which a large fraction is provided by demersal trawl fisheries (about 12 million tonnes) (Kelleher, 2005). Demersal trawl fisheries are mostly localized in Northern Europe and Northern American continental shelves.

In demersal otter trawl fisheries, a vessel tows a cone-shaped net with an average speed of often around three knots along the sea floor. The gear is connected to the vessel by towing warps (1 in Figure 1), which are winded on a winch on board of the vessel. Two otter boards, one of each side, (2 in Figure 1) open the net horizontally as soon as the vessel starts towing the gear (Valdemarsen et al., 2007). The trawl doors are connected to the net through bridles (3 in Figure 1). Both, the doors and the bridles arouse a herding effect on fish in the towing path into the direction of the trawl mouth, which is the open frontpart of the trawl (Glass, 2000). Fish near the trawl mouth are laterally surrounded by the wings (4 in Figure 1) and finally enter the net when the towing speed of the gear exceeds their swimming speed in towing direction. The vertical opening of the mouth is kept stable by two devises: a heavy ground rope (5 in Figure 1) and floating devices attached at the head rope (6 in Figure 1). By avoiding the ground rope, demersal fish are flushed into the net. Once entered the gear, fish passively drifts or actively swims through different sections of the trawl (7: trawl belly, 8: extension, Figure 1) until they reach the codend (9 in Figure 1). The codend is the final part of the net, where the total catch accumulates (Glass, 2000).

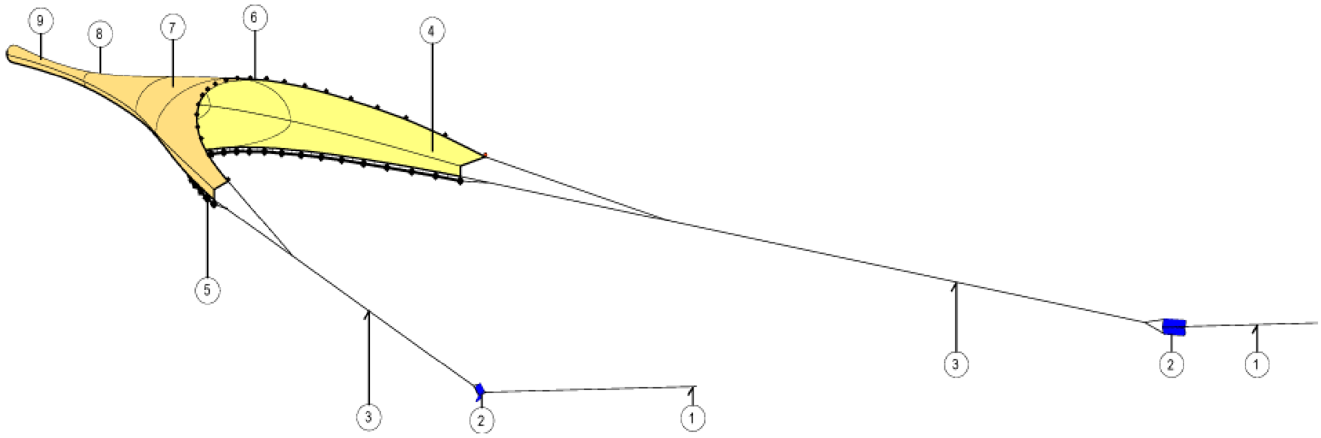

Figure 1: Main structure and components of a standard otter trawl ((1) towing warps; (2) otter boards; (3) bridles; (4) wings; (5) ground ropes; (6) head rope; (7) belly; (8) extension/ tunnel; (9) codend).

The demersal trawl fisheries target species living on or several meters above the seafloor (Valdemarsen et al., 2007), as for example cod (*Gadus morhua*), pollack (*Pollachius pollachius*), haddock (*Melanogrammus aeglefinus*), nephrops (*Nephrops norvegicus*) and several flatfish species (Kelleher, 2005). Fishing grounds inhabited by the target species usually present complex assemblages of fish and invertebrate populations. They are composed at the same time by different ages, sizes and species, many of them vulnerable to the commercial gears. As consequence, unwanted fish species and/or unwanted fish lengths classes are usually caught in demersal trawl fisheries besides the fishing targets. The catch fraction that is not the primary target of the fishing activities is defined by FAO as bycatch (Clucas and Nations, 1997). Once onboard, it is estimated that an important fraction of the bycatch, which fishermen do not want to land in, is thrown back to sea as discard. A recent global discard assessment estimates a discard rate averaging 20.8 % in finfish fisheries, very similar to what is estimated for all non-shrimp trawl fisheries (19,1 %) (Kelleher, 2005). Discarding can occur for different reasons acting alone or interacting each other (Rochet and Trenkel, 2005), for example the use of unselective fishing gears, or management measures which force the fishermen to discard a part of the catch in order to comply with them. For instance, this is the case with species *Minimum Landing Size* (*MLS*) regulations (Kelleher, 2005). The *MLS* sets minimum sizes for fish and shellfish species to be retained on board, transported or sold (European Commision, 2013). *MLS* are usually defined considering length of first maturity of the target species together with other considerations. For example, Baltic cod reaches sexual maturity an average length of 32 cm to 41 cm (Barot et al., 2002), and species *MLS* is set at 35 cm (European Commision a, 2014). Fish below *MLS* are illegal for landing. Therefore, fishermen are forced to discard undersized individuals. Since the discarded fish may be already dead or not survive this process (Kelleher, 2005), discarding is considered as a fishing practice which harms fish stocks and marine ecosystems (Catchpole et al., 2005).

1.2 Size selection in trawl gears

With the aim of maintaining or restoring fishing stocks, fishery management plans usually incorporate measures to minimize the bycatch of undersized fish. Among others, the improvement of commercial fishing gears is one of the most used strategies. A gear is named "size selective" for a given species when it minimizes the probability of catching small individuals while keeping the catchability of marketable classes. It is important that the selection takes place during towing since the survival possibilities of fish caught and subsequently discarded decreases significantly (Birkeland and Dayton, 2005).

Big efforts have been invested to reduce the catchability of small fish through the development of selective gears. Usually, fishing technologists focus their efforts on the development of new codends, since it is the part of the gear where the major part of the size selection takes place. This is, for example, the case in the cod-directed trawl fishery in the Baltic Sea (e.g. Glass, 2000; Madsen, 2007).

The selection of the codend is driven by two events. The first one is that the fish gets into contact with the meshes. The second event is the ability that a fish passes through the meshes, which depends on the relation between fish size and fish cross-section and the characteristics of codend meshes. To escape, fish with a given length or morphology has to physically pass through the codend meshes, else, the fish will be caught. It is therefore easy to see that the probability for a fish to be retained in the codend increases with the girth circumference. Girth circumference is strongly and often linearly related to fish body length (Wileman et al., 1996); even though this relationship can vary, fish length is easier and faster to measure. Hence, length is the most used measurement to experimentally describe codend selectivity (Wileman et al., 1996). On the other hand, the probability for a fish with a given length to escape can be altered by codend modifications (for example, altering mesh size, mesh geometry, twine thickness, the number of twines, number of meshes in circumference) (e.g. Glass, 2000; Glass and Wardle, 1995; Herrmann and O'Neill, 2006; Kim, 2013).

Traditionally, codends in commercial fisheries are made of diamond-shaped meshes (Madsen, 2007). It has been observed that during towing the longitudinal tension in the codend increases with catch volume (Glass, 2000). The consequence is that the diamond meshes are closed and the number of open meshes available for size selection is therefore reduced (Glass, 2000). A solution successfully tested and applied in different fisheries to avoid this mechanical problem is to rotate the mesh orientation by 90° so that they are kept open even under high tension (T90 meshes) (Glass, 2000). Small fish can now escape during the whole catch process (Glass, 2000; Madsen, 2007). In summary, the probability for a fish to escape through the codend meshes depends on whether the individual successfully contacts the mesh and how well it fits to the mesh opening.

The size selectivity of a gear can be analytically quantified by analyzing catch data from experimental fishing trials. It is of major interest for fishing technologists and fishing managers to know the probability for a fish with a given length to be retained in the codend. Therefore, the main aim of the experimental sea trials is to measure the proportion of fish retained in the codend relative to the number of fish which was able to escape through the codend meshes. The catch data in selectivity studies are therefore obtained following pre-defined experimental protocols to quantify (directly or indirectly) the number of fish retained in the codend and the number that escaped. Both, research vessels and commercial fishing vessels can be used to collect the data. The empirical observations are analyzed and usually represented by the so-called selection curves, which describes the probability for a fish to be retained in the codend conditioned to fish length (Figure 2) (Dickson et al., 1995; Wileman et al., 1996).

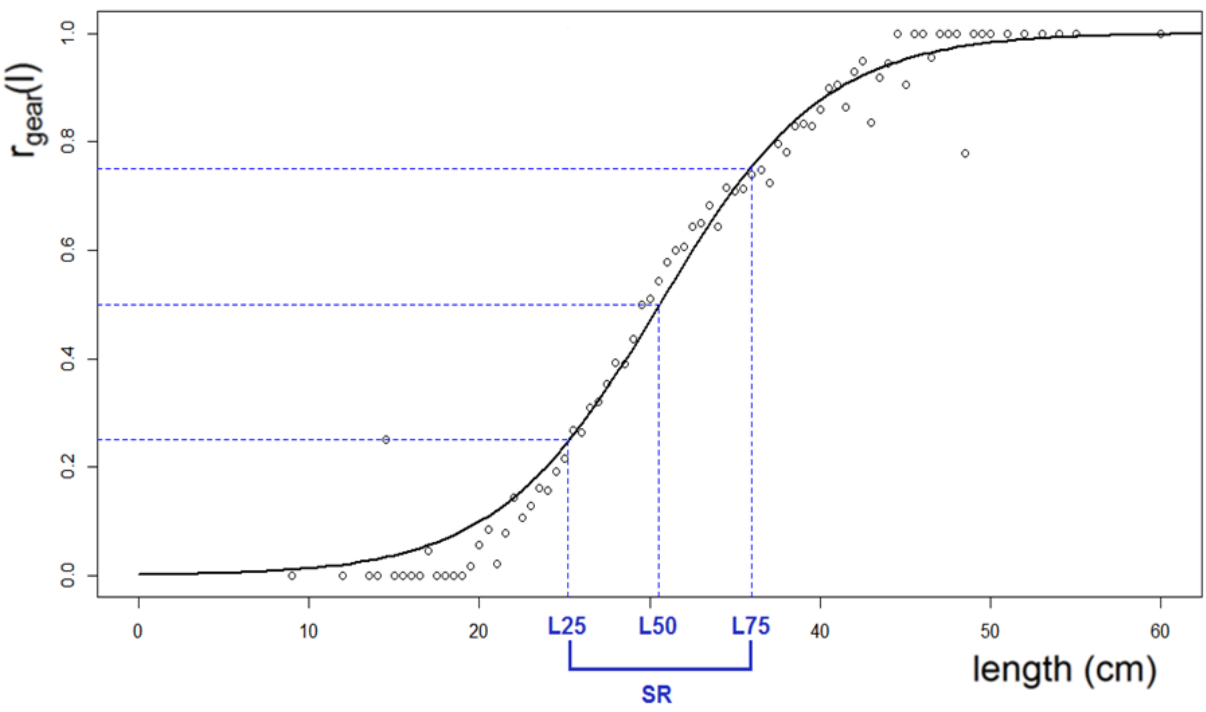

Figure 2: Example of a size selection curve of cod with experimental data (points) and selection parameters L50 and SR.

Size selection curves are normally summarized by two parameters allowing comparative studies between gear setups. The 50 % retention length (L50) is the length of a fish that has a probability of 50 % to be retained in the codend after it entered it. The second parameter is the selection range (SR). This is the difference in length between the probability of 25 % (L25) and 75 % (L75) retention in the codend. SR can be interpreted as the sharpness of selection (Wileman et al., 1996). Selection curves depend on the species which is investigated on and the used trawl gear. They are estimated by regression tools for binary data (Millar and Fryer, 1999; Wileman et al., 1996).

The increasing shape of the standard selection curve shown in Figure 2 represents well the current management paradigm in fishing management: minimize the probability of catching small fish while focusing the fishing efficiency on larger fish.

1.3 New hypothesis for better exploitation patterns

Even though the current strategy of focusing the fishing efficiency of trawls on large fish is well established in world fisheries, it is important to start considering alternative harvest patterns in order to have several options to use fisheries optimal and more sustainable. The alternative strategy proposed in the present study is based on recent findings in the reproductive fish biology. These findings give several good reasons to reduce the fishing pressure on large individuals. Firstly, older and therefore also larger individuals produce an exponential higher number of eggs, compared to younger individuals (Birkeland and Dayton, 2005). This can be explained by the fact that larger bodies have room for the development of larger ovaries (Hixon et al., 2014) and therefore a higher abundance of eggs (Figure 3).

Figure 3: Left: Comparison of two female cod with a length of 75 cm (top) and 30 cm (bottom) and their gonads (right) (photos taken by: M. Bleil, TI-OF).

Naturally, the chance that some larvae meet favorable conditions is increased by the number of eggs. Secondly, larvae produced by older individuals have a higher average chance to survive due to increased egg size and increased quality (Hixon et al., 2014). Additionally, older fish are more experienced in spawning and extend the spawning season (Birkeland and Dayton, 2005). This temporal spread leads to an increased probability that larvae encounter appropriate environmental conditions like increased food availability or reduced predator pressure (Hixon, Johnson, and Sogard 2014 (as cited in Cushing, 1990 and Bailey and Houde, 1989)). In turn, the removal of mainly large fish leads to earlier maturation and slower growth-rate due to the selection of genes and finally causes a fishery-induced evolution which results in maturation at younger age and smaller length (Garcia et al., 2012; Law, 2000; Law et al., 2015). Based on what is stated above, there are strong reasons in fishery management to think about different exploitation patters of fish stocks.

A good example to support the earlier argumentation can be found in the case of cod. Cod shows strong correlations between length, age and fecundity (Hixon et al., 2014; Marteinsdottir and Begg, 2002). *Gadus morhua* is economically the most important species in the Baltic Sea. Through harvesting mainly large cods, the number of eggs with a high quality is decreasing significantly. Therefore, it can be speculated that reducing the catches of old and large cod might lead to healthier fish populations.

In contrast to Berkeley et al. (2004), who assume that probably the only way to maintain a population with a working age structure is by establishing a network of marine reserves, this study presents an alternative strategy based on altering the selectivity of standard gear to reduce the fishing pressure on larger fish. This "alternative harvesting" ensures that all length classes are present and preferably distributed evenly. An alternative selectivity concept like the one proposed in this study can help to fish more sustainable by avoiding undersized fish as well as the largest fish from catches.

1.4 An attempt to achieve alternative harvesting in trawl fisheries through fishing technology

As explained in chapter 1.2, small fish can escape from the catch through mesh selection in the codend. However, the challenge of simultaneously avoiding small and large fish from catches cannot be addressed by means of codend selectivity alone. Therefore, alternative selective concepts are required to meet the aim of an alternative harvest pattern in trawl fisheries. This study presents the development and testing of different configurations of a new selectivity concept for trawl gears to achieve the alternative exploitation pattern mentioned in section 1.3. This pattern focuses on catching only medium sized individuals while avoiding small and large fish from catch.

The basic idea of this new selective concept relies on emulating the selectivity curves that can be found in passive gears, such as gillnets (Hovgård and Lassen, 2000). Gillnets are made of net panels fixed with anchors on the seafloor or float at an adjusted depth in the water column. As in the case of trawls, an important aspect defining gillnets selectivity is the mesh size, but contrary to traditional trawls, the fishing efficiency of gillnets is focused on medium length classes due to the selective events happening when a fish encounters the net:

1. Small fish (relative to the mesh size) can pass through the meshes.
2. Large fish (relative to the mesh size) cannot be entangled because they are too big to enter the mesh.
3. Medium sized fish which body cross-section fits to the mesh opening are entangled and therefore caught in the gear.

The mechanical sorting presented above is not available in standard trawl nets, since medium sized and large fish typically cannot escape and therefore are caught. The technological development presented in this study, attempts to emulate the full range of the selectivity idea from gillnet gears in trawl gears. Two well-known devices are combined in an experimental trawl gear to achieve this goal: grid and codend.

The first selective device used in the experimental gear is an adapted version of sorting grids tested in nephrops (*Nephrops norvegicus*) fisheries. A grid with vertical bars is installed ahead of the codend of the nephrops trawls to prevent fish bycatch. The bar space is large enough for small fish and nephrops to enter the codend but does not allow large fish to pass through. These fish can leave the gear through an outlet above the grid (Catchpole and Revill, 2007).

In the context of the present study, by mounting the grid in front of the codend it is intended to prevent catches of large fish. An optimal grid barspacing must be found in order to only allow the passage of small and medium-sized fish towards the codend, while big individuals not fitting through the bar spacing should be excluded by an excluder hole placed in the upper panel in front of the grid.

To get satisfying results in this first selection process, two major aspects should be considered: Firstly, fish should not escape through the escapement outlet without prior contact with the grid. Secondly, if the fish contacts the grid, they should try to pass through it. To satisfy the first point, the probability that a fish gets into contact with the grid (hereafter c_{grid}) should be as high as possible. Factors which can cause a low c_{grid} are a small grid area or very high amounts of fish entering the trawl at the same time (Sistiaga et al., 2010). Additionally, the grid angle might have an effect on the contact probability. Having a high c_{grid} but unsatisfying results of selectivity, the bar spacing has to be improved (Sistiaga et al., 2010). If it is too small, fish do not try to pass through it because it seems to be like a wall (wall-effect). It is an important goal to optimize c_{grid} to a maximal value so that the probability that a fish escapes through the escapement outlet without contacting the grid is minimized.

The second selection process intended in the experimental gear is located in the codend and uses the standard size selection based on mesh size and mesh orientation. It is only available for small and medium sized fish that passed through the grid. As in the case of the grid, optimal codend characteristics must be found in order allow the escapement of small fish keeping the catchability of medium-sized fish.

After developing the new concept, it was tested in the cod-directed fishery in the Baltic Sea. Since different settings of grid and codend are possible, the most suitable setup for the intended exploitation patterns has to be found. It also has to be taken into consideration that the results of these experiments might be affected by other factors like the presence of large amounts non-target species. Flatfish for example block the meshes of the codend due to their shape and prevent small roundfish from escaping. This study focuses on the analysis of the data collected on the SOLEA cruise 687 (March/April 2014) and shows that it is possible to change the traditional harvest pattern. Therefore, the influences of the different gear setups of codend, grid and escapement outlet have been tested to estimate their influence on this new selectivity concept.

2. Material and Methods

2.1 Gear description

The experimental gear (Figure 4) is based on a standard trawl model TV300/60. Different gear setups were considered for testing, each differing in the grids configuration and/or the codend. Two different T90 codends were used during the sea trials, distinguishing each other in mesh size. The first codend has the nominal mesh size (120 mm, stretched mesh opening), which legalized for this fishery. Since the length structure of the cod population in spring 2014 (derived from Baltic International Trawl Survey, ICES SD 24, 1st quarter 2014) mainly consisted of small cod, it was considered that 120 mm mesh size could be too big for the specific objectives of the study. Consequently, the second codend included in the experimental design has a smaller nominal mesh size of 105 mm. The codend was joined to the trawl belly through a net tunnel made of 60 mm mesh size, which can be considered as an extension of the codend. In this extension piece the grid was mounted. Four different grid configurations were considered for testing, differing each other by the bar spacing (42.5 mm and 50 mm) and/or vertical angle of attack (45° and 75°). To increase the probability that a fish gets into contact with the grid, a guiding panel (Figure 4) was installed in front of the grid. Since only small fish can pass through the grid, the big ones are expected to leave the net through the escapement outlet (EO). To make it less visible, especially for small fish, a rectangular piece of net, which was only fixed at the fore part of the EO, was used. The resulting masked escapement outlet (MEO) was not used in every setup. Mesh sizes (stretched mesh opening) of the codend were controlled using an OMEGA-gauge with 125 N stretching force (Fonteyne et al., 2007; EU Regulation no 517/2008) (Table 1).

Table 1: Mesh opening of different parts of the gear; nominal and measured with the OMEGA-gauge

compartment	nominal mesh size (in mm)	measured mesh size (in mm)
Belly	60	-
Extension	60	-
Codend 1	105	107
Codend 2	120	123
Cover	60	-

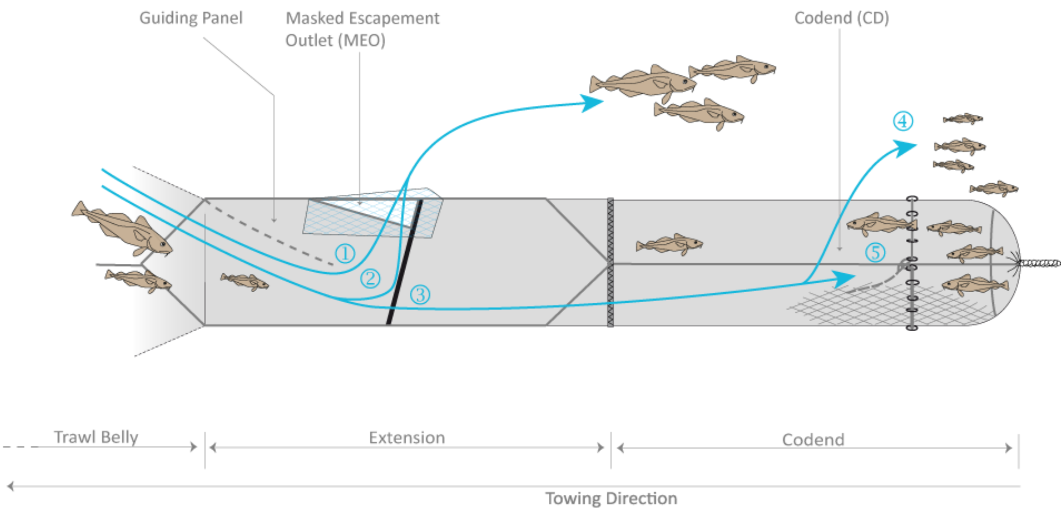

Figure 4: Illustration of experimental gear (belly part of the trawl is not shown) including numbers for the different traits a fish can take in of the selection devises grid and codend. 1) Fish does not contact the grid and escapes through the EO; 2) Fish contacts the grid but does not pass through and escapes through the EO; 3) Fish passes through the grid and enters the codend; 4) fish escapes through the meshes in the codend; 5) fish is caught in the codend.

Altogether, eight different setups were considered, varying each other in the mounting angle of the grid, bar spacing, presence of MEO and/or codend mesh size (Table 2).

Table 2: Specification of the different gear setups.

Setup	Bar space grid (in mm)	Angle grid (in °)	Mesh size codend (in mm)	MEO	Number of hauls	Date	Statistical analyses conducted/ possible
0	50	75	120	yes	3	14.3.2014	No
1	50	75	120	yes	11	17.-20.3.2014	Yes
2a	50	75	105	yes	11 (valid 9)	21.-23.3.2014	Yes
2b	50	75	105	yes	8	25.-26.3.2014	Yes
3	50	45	105	yes	2	24.3.2014	No
4	50	75	105	no	1	27.3.2014	No
5	42.5	75	105	no	10 (valid 9)	27.-29.3.2014	Yes
6	42.5	75	105	yes	10	30.3-1.4.2014	Yes
7	no grid	-	105	no	2	2.4.2014	No

2.2 Model for describing selection curves

The standard parametric models used to estimate standard size selection curves (compare Figure 2) assume a non-decreasing trend in the retention probability with increasing fish size. This is not the overall size selection process expected to occur in the experimental gear presented here, due to the combined selection process of grid and codend. Contrary to the standard case, small retention probabilities for small and large fish were expected. Therefore, the standard model structure needs to be adapted to the new demand. A more complex model than the one used to estimate the codend selection curve with (see chapter 1.2 and Figure 2) had to be implemented. This model has to be able to simultaneously account for the selection process expected to occur in the grid and the codend. This is done as follows:

$$(1)\quad r_{gear}(\mathrm{l}) = p_{grid}\left(l, C_{grid}, L50_{grid}, SR_{grid}\right) \times r_{codend}\left(l, L50_{codend}, SR_{codend}\right)$$

The *overall retention probability of the gear* (*$r_{gear}(l)$*) describes the probability for a fish to be caught in the codend. Once a fish enters the gear, *$r_{gear}(l)$* depends on the probability that it passes through the grid *($p_{grid}(l)$, passage probability through the grid)* towards the codend and that it is retained in the codend *($r_{codend}(l)$, retention probability in the codend, provided its entry)*. Note that both p_{grid}(l) and r_{codend}(l) and therefore also r_{gear}(l) are fish length-dependent functions. It is expected that large fish do not pass through the grid, thus do not enter the codend, leaving the trawl through the EO positioned above the grid, while small fish would escape through the codend meshes.

Contrary to the standard models, the proposed model (1) should be able to properly model the highest retention probability at medium length classes and lower probabilities at small and large length classes, based on the expected data from the experimental gear. Due to the assumed shape of *$r_{gear}(l)$*, the resulting selection curve is herein so-called *bellshape-curve.*

The selectivity functions on the right hand side of model (1) can be described separately since they characterize two different selectivity processes. *$r_{codend}(l)$* describes the probability that a fish of a given length is retained in the codend by means of size selection.

$p_{grid}(l)$ can be split into the probability that a fish efficiently contacts the grid *(c_{grid},, contact probability with the grid)* and that it is small enough to pass through the grid after contacting

it *(1-r_{grid}(l))*. Accordingly, the probability that a fish passes through the grid towards the codend can be described as:

$$(2)\quad p_{grid}\left(l, c_{grid}, L50_{grid}, SR_{grid}\right) = c_{grid} \times \left(1 - r_{grid}\left(l, L50_{grid}, SR_{grid}\right)\right)$$

Both p_{grid}(l) and r_{codend}(l) can be described separately by standard size selection models for trawl gears which are based on L50 and SR, described in chapter 1.2. All models proposed in Wileman et al. (1996) estimate increasing "S-shaped" selection curves to describe the expected increasing retention probability with increasing fish length. In the present study the original selectivity models were adapted to better account with the selectivity of the grids; contrary to the codend selectivity, it is expected that small fish have a higher probability to pass through the grid than large individuals. Combining the selection of grid and codend, the resulting curve is bell-shaped with low retention probabilities for small and large fish. Based on Wileman et al. (1996), three different selectivity models were taken into account, which are typically used in the size selection of trawl gears: *Logit, Gompertz and Richard*. Each model has its own characteristics (Wileman et al., 1996):

Logit/Logistic: cumulative distribution function of a logistic random variable, symmetrical in point of inflection

Gompertz/extreme value: asymmetric cumulative distribution function, inflection point at 37 % of the total saturation

Richard: expansion of the logit function with asymmetrical parameter δ; when δ>1 the curve has a longer tail on the left of L50, when δ<1 longer tail on the right of L50 and when δ=1 it is reduced to the logistic curve

Since the functions above use the parameter *a* and *b*, it is necessary to estimate the parameters L50 and SR from an additional function (Table 3).

Table 3: Different S-shaped models with corresponding function and selection parameters L50 and SR (following Wileman et al., 1996)

model	function	L50	SR
Logit	$r(l) = (\frac{\exp(a + b * l)}{1 + \exp(a + b * l)})$	$L50 = -\frac{a}{b}$	$SR = \frac{2.197}{b}$
Gompertz	$r(l) = \exp(-\exp(-(a + b * l)))$	$L50 = \frac{0.3665 - a}{b}$	$SR = \frac{1.573}{b}$
Richard	$r(l) = \frac{\exp(a + b * l)}{1 + \exp(a + b * l)}^{\frac{1}{\delta}}$	$L50 = \frac{logit(0.5)^{\delta} - a}{b}$	$SR = \frac{logit(0.75^{\delta}) - logit(0.25^{\delta})}{b}$

2.3 Model selection and Inference

To calculate the selection parameters $L50_{grid}$, SR_{grid}, $L50_{codend}$ and SR_{codend}, firstly the parameter c_{grid}, a_{grid}, b_{grid}, a_{codend} and b_{codend} for the overall selection model had to be estimated. Using the Maximum Likelihood estimation (Formula 3), the parameters of the model are estimated, so that the best possible fitting to the experimental data is found (Millar and Fryer, 1999). Therefore, the following function has to be minimized, which means that the likelihood for the observed data is maximized:

$$(3) \quad -\sum_l \sum_{j=1}^{m} \Big\{ n_{TC,l,j} \times ln\left(1.0 - p_{grid}\left(l, C_{grid}, L50_{grid}, SR_{grid}\right)\right) + \left(n_{CC,l,j} + n_{CD,l,j}\right) \times ln\left(p_{grid}\left(l, C_{grid}, L50_{grid}, SR_{grid}\right)\right) + n_{CC,l,j} \times ln\left(1.0 - r_{codend}(l, L50_{codend}, SR_{codend})\right) + n_{CD,l,j} \times ln\left(r_{codend}(l, L50_{codend}, SR_{codend})\right)\Big\}$$

The function sums over the hauls j (from 1 to m) and over the length classes, which are each 1 cm wide. The number of individuals in the different compartments is denoted by n.

Therefore, three models for grid as well as codend selection were combined. Altogether, nine different models for the overall size selection of the trawl were considered (see chapter 2.2). In order to find the model which fits best to the data, the model with the lowest AIC-value (Akaike Information Criterium) was chosen. The goodness of fit of the model was assessed by checking the p-value and the model-deviance regarding the degree of freedom (DOF). The DOF was calculated by subtracting the number of parameters from the number of length classes per setup. To reject the null hypothesis that the model does not fit the data well, the degrees of freedom has to be higher than the Chi Deviance and the p-value has to be higher than 0.05. Further, the data were tested for overdispersion. Overdispersion appears when the variance of the data is higher than expected from the model. In addition, the estimated curves were checked whether they reflected the length-based trend of the data well.

Bootstrapping was used to estimate the percentile Confidence Intervals for both, the selectivity parameters and the selection curves for each experimental setup. The montecarlo technique applied here follows a blockwise resampling scheme to account for the within-between haul variation naturally observed in selectivity studies. A description of the resampling scheme is summarized below:

1. After a random haul is extracted from the sample of hauls, it is replaced (resampling), so that it can be chosen again.

2. This resampling method is applied for each compartment (in this study three compartments, see chapter 2.4) independently for each haul $h_1*,\ldots,h_N*$ selected in 1. This step serves to receive new pseudo-hauls ($h_1**,\ldots,h_N**$)
3. The experimental data are pooled over the pseudo-hauls obtained in 2. ($H^*=\sum_{i=1}^{n} h_i^{**}$)
4. A set of selectivity curves ($p^*_{grid}(l)$, $r^*_{codend}(l)$, *and overall* $r^*_{gear}(l)$) and related selectivity parameters ($L50^*_{grid}$, SR^*_{grid}, $L50^*_{codend}$ and SR^*_{codend}) are estimated from H^*.
5. Steps 1 to 4 are repeated a high number of times (x1000 in the resent study), so that a population of selectivity curves and related parameters is estimated from the simulated data.

6. Finally, the confidence intervals are estimated by using the percentiles of the bootstrap distribution (step 5) for each of the selection parameter or selection curve (θ) separately:

   (4) $\theta^*_{\alpha/2}$; $\theta^*_{1-\alpha/2}$, with α being the quantile 0.05.

Equations (1), (2) and (3), original selectivity models (Table 3), and the bootstrap scheme showed above where written in R (R Development Core Team, 2008). The estimation of the selectivity parameters and selection curves was carried out by using the optimization algorithms available in R package optimx (Nash et al., 2014).

2.4 Data collection

The experiments were carried out onboard of the German Fishery Research Vessel (FRV) “Solea” (42.4 m LOA, 1780 kW, stern trawler) from 14th March – 04th April 2014 with Juan Santos from the Thünen-Institute of Baltic Sea fisheries as cruise leader. I volunteered on this cruise as part of the scientific team. The 687th cruise of FRV “Solea” started from Rostock to the Western Baltic Sea. On the first day, the fishing grounds were located near Warnemünde to test the physical behavior of the experimental gear. During the first five days, the vessel fished in the Mecklenburger Bay (ICES SD 22). Later, the vessel moved into the Arkona Basin (ICES SD24), which is located northeast of Rügen Island (Figure 5). The exact operational informations were collected using the central data distribution system of the vessel. These data contain, amongst others, information about the geographical coordinates of the fishing stations, towing times, depth and meteorological data.

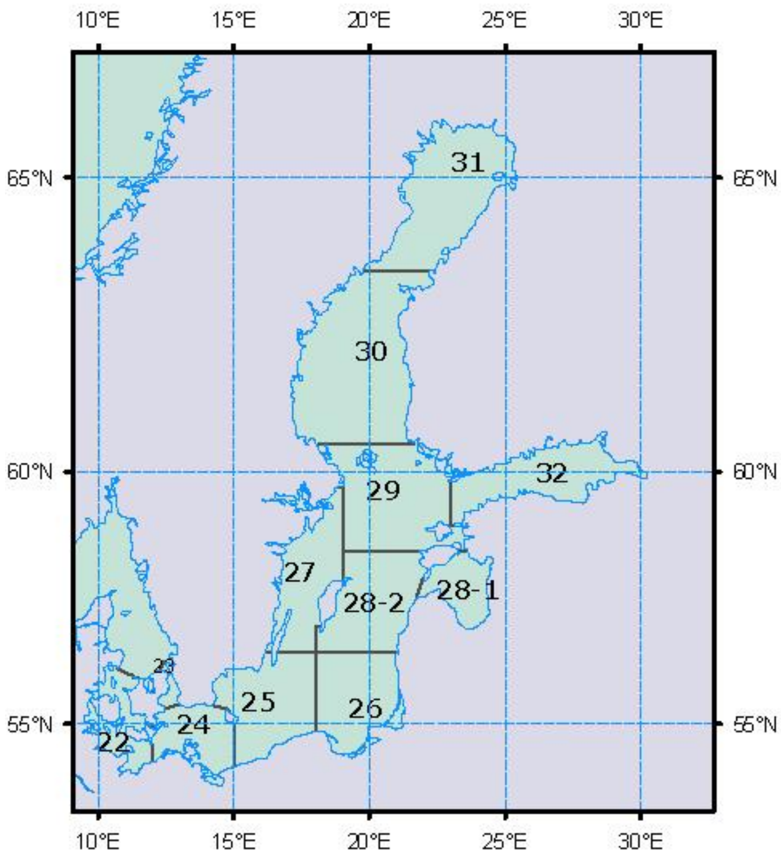

Figure 5: Map of the Baltic Sea with ICES subdivisions (from fao.org). The area of investigation was in subdivision 22 and 24.

To separately collect the fish caught in the codend, and fish which escaped through the two selection devices, a three-compartment setup was used:

a) Grid cover (GC): collecting the fish which escaped through the escapement outlet (EO),
b) Codend cover (CC): collecting the fish which escaped through the codend and
c) Codend (CD): collecting the fish which was finally caught in the codend.

Therefore, the cover method (Wileman et al., 1996) was applied and small diamond mesh nettings were used over the EO (grid cover, GC) and the codend (codend cover, CC) to catch the escaped fish. The nominal mesh size of these covers was 60 mm. Kites were used to keep the two covers away from the test codend and the EO (Figure 6).

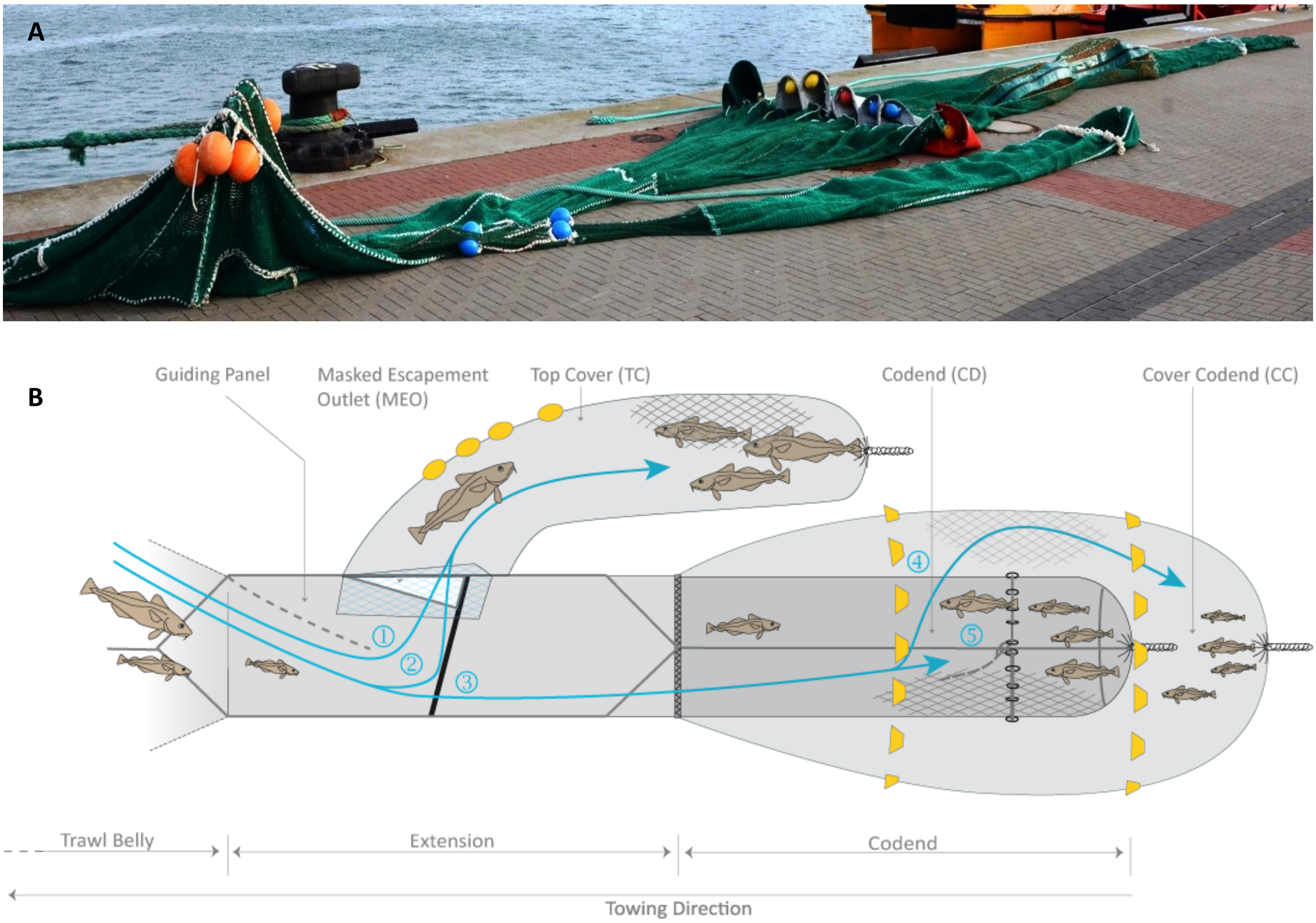

Figure 6: A) Photo of the gear used in the experiment (tunnel and codend). B) Illustration of the three-compartment setup of the gear with yellow buoys and kites. 1) Fish does not contact the grid and escapes through the EO; 2) Fish contacts the grid but does not pass through and escapes through the EO; 3) Fish passes through the grid and enters the codend; 4) fish escapes through the meshes in the codend; 5) fish is caught in the codend.

A total of 55 hauls were conducted during the cruise. Each haul reached the deck separated into the three compartments GC, CD and CC. Each compartment was sorted by species and was weighted afterwards by the scientific staff onboard. The total size of each fish was measured to the nearest half centimeter below, using electronic length-measurement boards.

2.5 Underwater observation

For underwater observation, GoPro cameras (GoPro Hero 3 HD cameras without artificial light) were installed at different positions in the trawl. They were used to control whether the gear and the covers operate correctly in the desired manner. In this case the videos were analyzed directly onboard. Additionally, they were used to observe how fish reacts near the selection devises. To not change the light conditions underwater which might lead to a change in the fish behavior, cameras without artificial light were used. The videos were analyzed qualitative and abnormalities were minded.

3. Results

3.1 Gear setups and operational information

Setup 0 served as trial to optimize the stability of the gear and the three compartments. In the course of testing, it was found that some fish accumulated in front of the grid and did neither use the escapement outlet nor the grid to enter the codend. After heaving, these fish were still in front of the grid (Figure 7). Therefore, an additional catch compartment, TU (tunnel), was introduced, which will not be considered in further statistical analyses, due to its minor contribution to the total catch. However, it was investigated on in the qualitative analyses of underwater (UW) video materials.

Figure 7: Photography of the grid section while heaving the net onboard. Fish accumulate in front of the grid (right side) and do not use the escapement outlet nor enter the codend.

Thereafter, the actual fishing trials started. The grid of setup 1 had 50 mm bar spacing and was mounted at an angle of 75 °. The codend had a nominal mesh size of 120 mm and a net panel masked the escapement outlet. Setup 2a had a reduced mesh size in the codend (105 mm) because of the length structure of the cod population mentioned above. Due to the reduction of the grid angle from 75 ° to 45 ° in setup 3, the height of the tunnel was reduced significantly. This net behavior could confound the effect of reducing the angle of attack of the grid. As consequence, setup 3 is invalid for further statistical analyses and it was only used to observe the fish behavior in relation with a reduced grid angle, by using the UW video recordings collected. The observations from setup 3 also showed a deformation of the grid due to the continuous use. This deformation, affecting the grid shape and therefore also the bar spacing, was fixed onboard. Additional eight hauls were conducted with setup 2, named as setup 2b since the grid was not in optimal conditions after reparation. In setup 4, the net panel which masked the outlet was removed. Again the grid was deformed heavily so that only one haul was performed. For this reason, setup 4 is not valid for statistical analysis. After that, the damaged grid was removed and replaced by a new one with smaller grid spacing (42.4 cm). Ten hauls were conducted with this setup 5. In setup 6 the net panel in front of the escapement outlet was mounted in again and tested in ten hauls. In setup 7, the grid was removed and two hauls testing the selection of the codend were performed. Due to the limited number of hauls, this setup is not valid for statistical analyses. Altogether, setups 1, 2a, 2b, 5 and 6 are valid and were used for further statistical analyses.

Altogether, we conducted 47 valid hauls in five valid setups in the Mecklenburg Bay (ICES SD 22) and Arkona Sea (ICES SD 24). Fishing depth varied between 13.8 m and 47.3 m. Towing duration varied between 50.3 min and 120 min. Additional operational information as well as the number and the catch weight of cod in the different compartments are listed in Table 4.

Table 4: Operational information of valid hauls (information when the gear touches the seafloor) and cod (number(weight)) in different compartments.

Haul	Setup	Area	Date	Towing duration (min)	Latitude	Longitude	Depth (m)	Cod in different compartments (number of cod (catch weight)) GC	CD	CC
4	1	Mecklenburger Bay	17.03.2014	120	54°12.276N	011°59.550E	15.2	28 (12.65)	84 (44.01)	632 (181.03)
5	1	Mecklenburger Bay	17.03.2014	120	54°12.281N	011°59.667E	15.2	38 (23.05)	101 (45.63)	938 (266.49)
6	1	Mecklenburger Bay	18.03.2014	120	54°12.246N	012°00.850E	14.2	49 (10.87)	94 (48.51)	200 (49.09)
7	1	Mecklenburger Bay	18.03.2014	120	54°12.213N	011°49.147E	20.8	67 (34.92)	141 (81.84)	370 (118.13)
8	1	Mecklenburger Bay	18.03.2014	120	54°12.226N	012°01.075E	14.3	33 (28.39)	214 (133.94)	1070 (476.72)
9	1	Mecklenburger Bay	19.03.2014	120	54°12.248N	012°00.927E	14.3	115 (60.70)	98(51.10)	12 (3.81)
10	1	Mecklenburger Bay	19.03.2014	120	54°12.291N	011°48.511E	21.3	356 (159.08)	156 (81.82)	325 (121.54)
11	1	Mecklenburger Bay	19.03.2014	120	54°12.316N	012°00.212E	14.8	58 (30.10)	165 (95.79)	606 (243.69)
12	1	Mecklenburger Bay	20.03.2014	120	54°12.217N	012°00.968E	13.8	370 (160.47)	400 (142.92)	1099 (367.60)
13	1	Mecklenburger Bay	20.03.2014	120	54°12.669N	011°46.501E	23.5	11 (3.53)	163 (77.05)	10 (2.751)
14	1	Mecklenburger Bay	20.03.2014	120	54°12.433N	011°58.131E	16.8	870 (411.89)	110 (54.84)	379 (145.21)
15	2a	Mecklenburger Bay	21.03.2014	120	54°12.227N	012°00.860E	14.0	321 (137.65)	835 (402.34)	657 (202.11)
16	2a	Mecklenburger Bay	21.03.2014	120	54°12.568N	011°47.101E	22.5	375 (396.62)	1151 (433.63)	751 (246.03)
17	2a	Mecklenburger Bay	21.03.2014	90	54°12.254N	012°00.422E	14.5	953 (176.15)	839 (526.22)	741 (238.89)
19	2a	Arkona Sea SD 24	22.03.2014	90	54°42.635N	013°29.785E	40.6	38 (16.4)	364 (148.26)	138 (32.10)
20	2a	Arkona Sea SD 24	22.03.2014	120	54°50.315N	013°27.635E	45.8	608 (239.47)	966 (418.59)	396 (115.05)
21	2a	Arkona Sea SD 24	22.03.2014	120	54°52.660N	013°15.529E	45.2	197 (80.44)	649 (254.39)	634 (147.40)
23	2a	Arkona Sea SD 24	23.03.2014	120	54°52.610N	013°15.166E	45.2	742 (331.48)	424 (167.88)	268 (63.46)
24	2a	Arkona Sea SD 24	23.03.2014	120	54°52.540N	013°30.885E	46.9	647 (225.77)	487 (266.00)	333 (104.99)
27	2b	Arkona Sea SD 24	25.03.2014	90	54°43.108N	013°34.162E	37.8	1620 (375.23)	430 (119.12)	1045 (167.72)
28	2b	Arkona Sea SD 24	25.03.2014	90	54°46.249N	013°27.203E	42.1	1082 (234.12)	260 (143.02)	634 (91.39)
29	2b	Arkona Sea SD 24	25.03.2014	90	54°52.708N	013°17.896E	45.9	1158 (364.82)	491 (170.64)	482 (107.24)
30	2b	Arkona Sea SD 24	25.03.2014	83	54°43.277N	013°25.720E	46.7	566 (147.83)	361 (122.82)	288 (71.16)
31	2b	Arkona Sea SD 24	26.03.2014	90	54°42.895N	013°34.491E	37.9	4 (2.63)	378 (154.89)	291 (72.39)
32	2b	Arkona Sea SD 24	26.03.2014	90	54°47.130N	013°27.431E	44.2	1 (3.55)	599 (222.65)	845 (197.82)
33	2b	Arkona Sea SD 24	26.03.2014	90	54°52.675N	013°15.017E	45.6	354 (113.73)	330 (110.80)	223 (44.93)
34	2b	Arkona Sea SD 24	26.03.2014	120	54°52.483N	013°23.161E	46.4	481 (140.18)	921 (318.21)	1155 (232.47)
36	5	Arkona Sea SD 24	27.03.2014	89	54°52.545N	013°22.613E	46.0	2012 (730.40)	281 (89.51)	193 (47.96)
37	5	Arkona Sea SD 24	27.03.2014	90	54°53.121N	013°33.527E	47.1	2197 (866.75)	603 (210.44)	599 (140.91)
38	5	Arkona Sea SD 24	28.03.2014	90	54°43.195N	013°34.093E	38.1	2022 (419.53)	495 (130.74)	788 (136.16)
39	5	Arkona Sea SD 24	28.03.2014	60	54°52.556N	013°25.866E	46.6	501 (212.73)	139 (47.07)	21 (3.44)
40	5	Arkona Sea SD 24	28.03.2014	90	54°53.987N	013°34.671E	47.3	1503 (567.26)	272 (102.73)	334 (68.05)
41	5	Arkona Sea SD 24	28.03.2014	50	54°52.502N	013°22.777E	46.6	232 (31.31)	97 (27.45)	47 (7.97)
42	5	Arkona Sea SD 24	29.03.2014	90	54°45.153N	013°30.800E	40.4	937 (267.29)	801 (261.80)	1339 (270.32)
43	5	Arkona Sea SD 24	29.03.2014	90	54°49.402N	013°28.001E	45.3	1121 (498.98)	324 (121.69)	692 (133.29)
45	5	Arkona Sea SD 24	29.03.2014	90	54°51.827N	013°25.742E	46.4	587 (211.00)	485 (168.53)	652 (106.98)
46	6	Arkona Sea SD 24	30.03.2014	90	54°43.404N	013°33.747E	37.6	2609 (622.69)	419 (100.70)	561 (97.54)
47	6	Arkona Sea SD 24	30.03.2014	90	54°48.038N	013°27.612E	44.3	401 (154.89)	330 (124.15)	540 (106.86)
48	6	Arkona Sea SD 24	30.03.2014	90	54°52.642N	013°20.167E	45.8	471 (159.02)	90 (25.60)	99 (16.84)
49	6	Arkona Sea SD 24	31.03.2014	90	54°42.824N	013°34.622E	37.3	1651 (218.20)	535 (91.79)	964 (168.32)
50	6	Arkona Sea SD 24	31.03.2014	90	54°46.951N	013°27.425E	43.3	1205 (359.43)	293 (135.75)	514 (102.44)
51	6	Arkona Sea SD 24	31.03.2014	90	54°52.633N	013°14.144E	44.9	660 (218.20)	125 (32.75)	55 (11.33)
52	6	Arkona Sea SD 24	31.03.2014	90	54°52.668N	013°16.221E	45.4	158 (66.40)	180 (53.72)	102 (19.72)
53	6	Arkona Sea SD 24	01.04.2014	90	54°43.310N	013°33.948E	38.0	1924(526.10)	567 (167.65)	532 (81.68)
54	6	Arkona Sea SD 24	01.04.2014	90	54°44.889N	013°31.222E	39.8	1303 (427.09)	844 (271.17)	967 (189.86)
55	6	Arkona Sea SD 24	01.04.2014	90	54°52.615N	013°19.299E	45.7	551 (199.57)	104 (37.15)	70 (14.06)

3.2 Description of the catch

During the SOLEA cruise a total amount of 30297.28 kg fish was caught in valid setups, whereof 24920.93 kg was cod (Table 5).

Table 5: Most caught species in kg separated into valid hauls.

species	Setup 1	Setup 2a	Setup 2b	Setup 5	Setup 6	total
Cod (*Gadus morhua*)	3901.91	5764.52	3737.59	6367.47	5149.44	24920.93
Flounder (*Platichthys flesus*)	91.01	471.76	450.19	653.52	591.72	2258.20
Plaice (*Pleuronectus platessa*)	83.00	197.00	113.00	140.76	184.67	718.43
Whiting (*Merlangius merlangus*)	26.47	359.02	81.75	164.79	120.09	752.12
Turbot (*Scophthalmus maximus*)	56.49	25.51	3.52	6.43	14.29	106.24
Dab (*Limanda limanda*)	844.04	345.25	5.71	3.86	6.43	1205.29
Saithe (*Pollachius virens*)	0.32	121.60	12.81	46.70	25.53	206.96
total	5003.24	7284.66	4404.57	7383.53	6092.17	30168.17

3.3 Model selection

In the following statistical analysis only cod is regarded, since they are the main targeted species in this area. It was possible to estimate all nine models for the valid setups. Considering the AIC-value, the best model for setup 1, 5 and 6 for both grid and codend was the Richards model (see chapter 2.2). Setup 2a and Setup 2b can be described best with the Gompertz model (see chapter 2.2) for the grid and the Richards model for the codend (Table 6).

Table 6: Parameters for each setup and model. Models are abbreviated (first letter: model for grid selection, second letter: model for codend selection, L: Logit, G: Gompertz, R: Richards). Best model for each setup in bold.

Setup	Model	Maximum Likelihood	Chi Deviance	p-value	AIC	Overdispersion-parameter	DOF
Setup 1	LL	8372.73	144.18	0.001	16745.46	1.50	91
	LG	8389.08	172.27	P<0.000	16778.16	1.80	91
	LR	8370.90	141.29	0.002	16741.80	1.47	90
	GL	8375.04	144.93	0.001	16750.08	1.51	91
	GG	8391.39	173.16	P<0.000	16782.77	1.80	91
	GR	8373.21	141.73	0.002	16746.42	1.48	90
	RL	8372.73	144.21	0.001	16745.46	1.50	90
	RG	8389.08	172.78	p<0.000	16778.15	1.80	90
	RR	**8389.08**	**141.08**	**0.002**	**16741.79**	**1.47**	**89**
Setup 2a	LL	13537.52	113.83	0.033	27075.04	1.29	83
	LG	13528.54	93.73	0.318	27057.08	1.07	83
	LR	13528.53	94.08	0.309	27057.06	1.07	82
	GL	13534.26	118.97	0.016	27068.52	1.35	83
	GG	13525.28	98.61	0.206	27050.56	1.12	83
	GR	**13525.27**	**98.31**	**0.212**	**27050.54**	**1.12**	82
	RL	13534.27	118.92	0.016	27068.53	1.35	82
	RG	13525.28	101.14	0.160	27050.57	1.15	82
	RR	13525.28	98.21	0.214	27050.61	1.12	81
Setup 2b	LL	14198.46	112.75	0.020	28396.92	1.34	79
	LG	14177.11	93.76	0.219	28354.22	1.12	79
	LR	14176.85	92.38	0.249	28353.70	1.10	80
	GL	14196.04	107.87	0.041	28392.08	1.28	79
	GG	14174.69	89.27	0.327	28349.38	1.06	79
	GR	**14174.43**	**87.81**	**0.367**	**28348.86**	**1.05**	80
	RL	14196.04	105.34	0.058	28392.09	1.25	80
	RG	14178.93	99.45	0.120	28357.87	1.18	80
	RR	14178.93	91.55	0.269	28348.87	1.09	79
Setup 5	LL	17037.49	93.30	0.777	34074.97	1.04	85
	LG	22795.79	7256.81	p<0.000	34041.26	80.63	85
	LR	17020.31	80.80	0.631	34040.63	0.90	84
	GL	17049.54	106.62	0.484	34099.08	1.19	85
	GG	22560.85	7203.47	p<0.000	45121.71	80.04	85
	GR	17032.37	94.24	0.313	34064.73	1.05	84
	RL	17028.83	97.60	0.476	34057.65	1.08	84
	RG	22794.78	7254.59	p<0.000	45589.57	80.61	84
	RR	**22794.78**	**79.06**	**0.499**	**34023.31**	**0.88**	**83**
Setup 6	LL	17074.16	80.64	0.699	34148.32	0.92	83
	LG	17067.51	83.49	0.616	34135.01	0.95	83
	LR	17066.10	77.78	0.774	34132.20	0.88	82
	GL	17077.07	89.52	0.435	34154.14	1.02	83
	GG	17070.42	92.15	0.360	34140.84	1.05	83
	GR	17069.01	86.39	0.529	34138.03	0.98	82
	RL	17073.80	78.78	0.749	34147.60	0.90	82
	RG	17067.15	80.82	0.694	34134.50	0.92	82
	RR	**17067.15**	**75.42**	**0.828**	**34131.49**	**0.86**	**81**

Since the Maximum-Likelihood function minimizes the square sum of the residuals of the model, a small value means that the model fits the data well. Only setup 5 and 6 show Chi-Deviance values higher than the degree of freedom (DOF). The DOF varied within and between hauls because they depend on the number of length classes per setup and the number of parameters used. The p-values for the Chi-Deviance for setup 2a, 2b, 5 and 6 are significantly higher than 0.05. Therefore, the null-hypothesis, that the models do not fit the data, can be neglected. Setup 1 has a p-value which is smaller than 0.05. Overdispersion can be considered as the reason for the poor fit statistics. However, the model curves do not show systematic patters of deviance and fit the experimental data well. That is why the models can be used confidently for describing the size selection in the experimental codend.

3.4 Comparison of setups

The number of valid hauls per setup differed between eight and eleven (Table 7).

Table 7: Selectivity parameters describing the size selection for grid and codend for each setup after choosing the best fitted model; 95 % confidence intervals in parenthesis; DOF: degree of freedom.

Selection device	Parameter	Setup 1	Setup 2a	Setup 2b	Setup 5	Setup 6
Grid	C_{grid}	0.83 (0.71-0.99)	0.73 (0.64-0.83)	0.63 (0.51-0.99)	0.94 (0.43-0.99)	0.62 (0.45-0.96)
	$L50_{grid}$	51.08 (44.03-55.11)	47.85 (46.32-50.20)	54.95 (39.54-1361.80)	28.51 (23.26-38.30)	35.84 (24.14-40.05)
	SR_{grid}	11.38 (4.93-32.73)	8.22 (5.83-12.59)	12.52 (0.83-241.93)	27.81 (7.25-35.66)	17.60 (9.86-35.74)
	Model	Richards	Gompertz	Gompertz	Richards	Richards
Codend	$L50_{codend}$	42.04 (38.51-44.31)	29.78 (28.29-31.20)	30.32 (29.31-31.71)	29.57 (28.64-30.22)	28.60 (27.06-30.03)
	SR_{codend}	12.03 (9.76-17.88)	11.11 (10.11-12.00)	10.14 (8.17-13.12)	9.55 (8.23-11.59)	10.24 (8.80-12.09)
	Model	Richards	Richards	Richards	Richards	Richards
	p-value	0.002	0.212	0.37	0.79	0.83
	Deviance	141.08	98.307	87.81	79.07	75.42
	DOF	89	82	78	83	81
	number of valid hauls	11	9	8	9	10

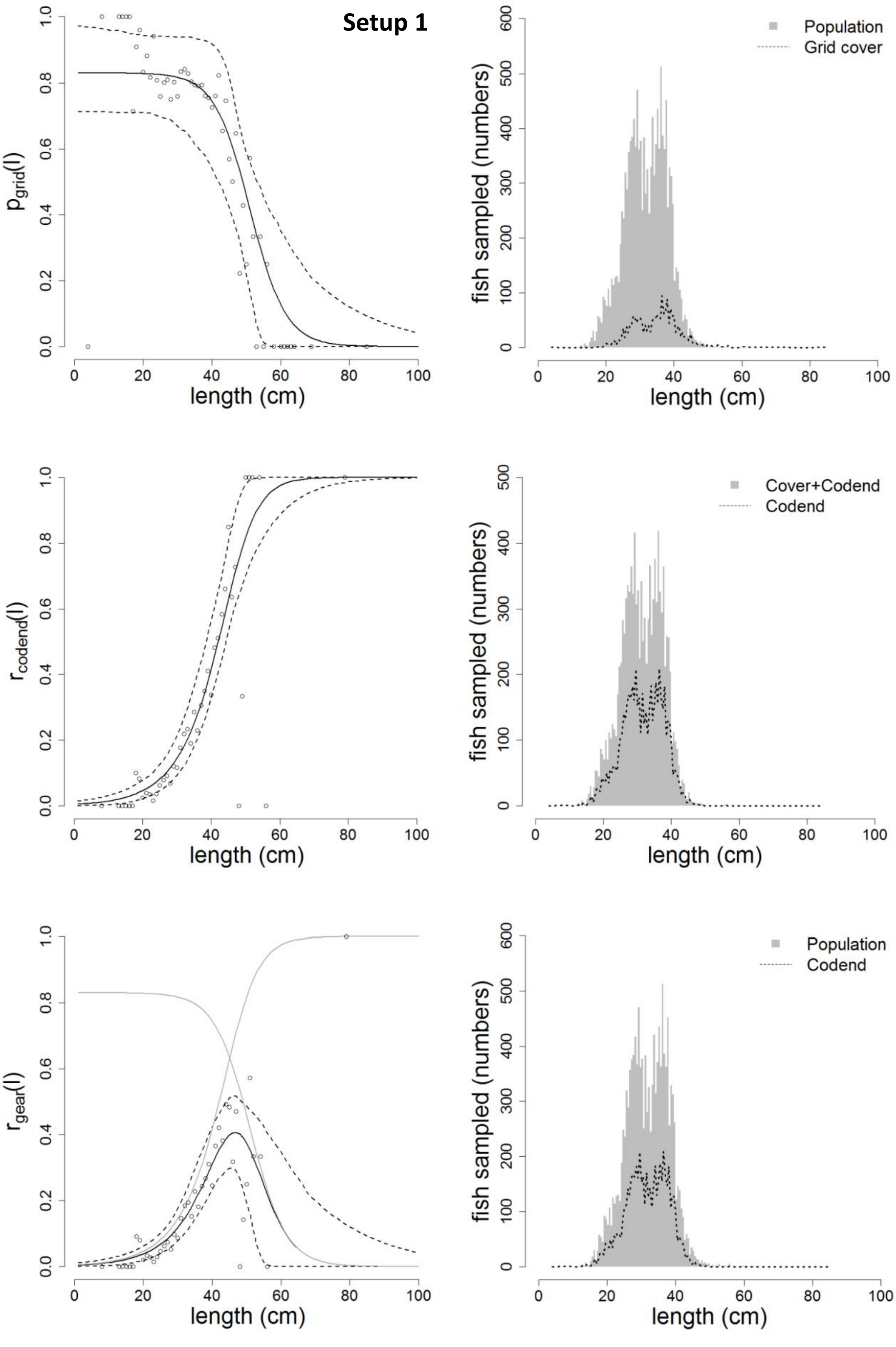

Figure 8: Setup 1 (50 mm bar spacing, 120 mm mesh size, with MEO); Left: Size selection curves of the different selection devices with 95% confidence Intervals (dots show experimental data, grey lines show selection curves of grid and codend). Right: Number of cod in the different compartments (dotted line: caught cod in the compartments, grey shaded area: number of cod entering the gear). Top: Selection of the 50 mm bar-spaced grid, with MEO. Middle: selection in the T90 120 mm codend. Below: Combined selection of grid and codend.

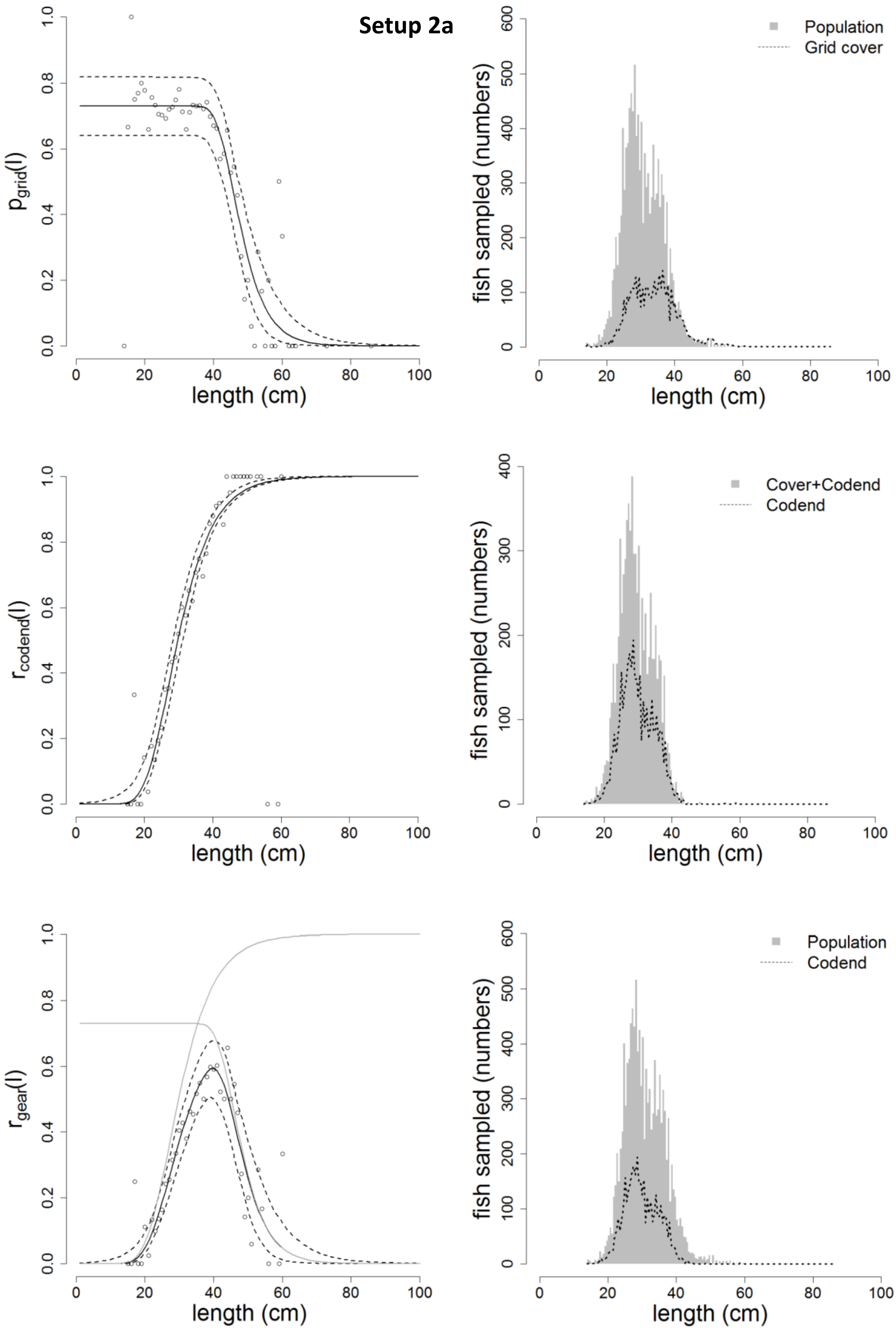

Figure 9: Setup 2a (50 mm bar spacing, 105 mm mesh size, with MEO); Left: Size selection curves of the different selection devices with 95% confidence Intervals (dots show experimental data, grey lines show selection curves of grid and codend). Right: Number of cod in the different compartments (dotted line: caught cod in the compartments, grey shaded area: number of cod entering the gear). Top: Selection of the 50 mm bar-spaced grid, with MEO. Middle: selection in the T90 105 mm codend. Below: Combined selection of grid and codend.

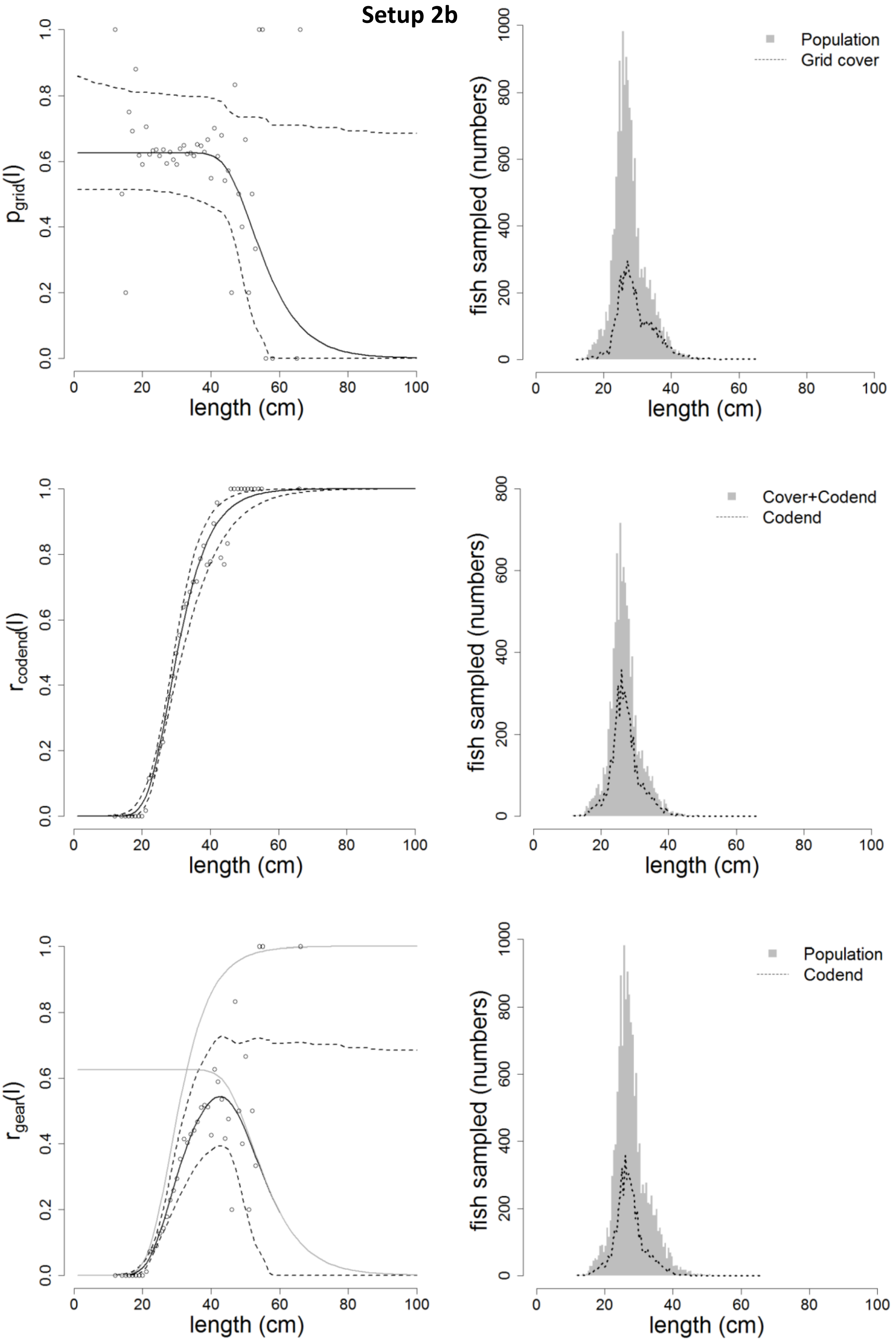

Figure 10: Setup 2b (50 mm bar spacing, 105 mm mesh size, with MEO); Left: Size selection curves of the different selection devices with 95% confidence Intervals (dots show experimental data, grey lines show selection curves of grid and codend). Right: Number of cod in the different compartments (dotted line: caught cod in the compartment, grey shaded area: number of cod entering the gear). Top: Selection of the 50 mm bar-spaced grid, with MEO. Middle: selection in the T90 105 mm codend. Below: Combined selection of grid and codend.

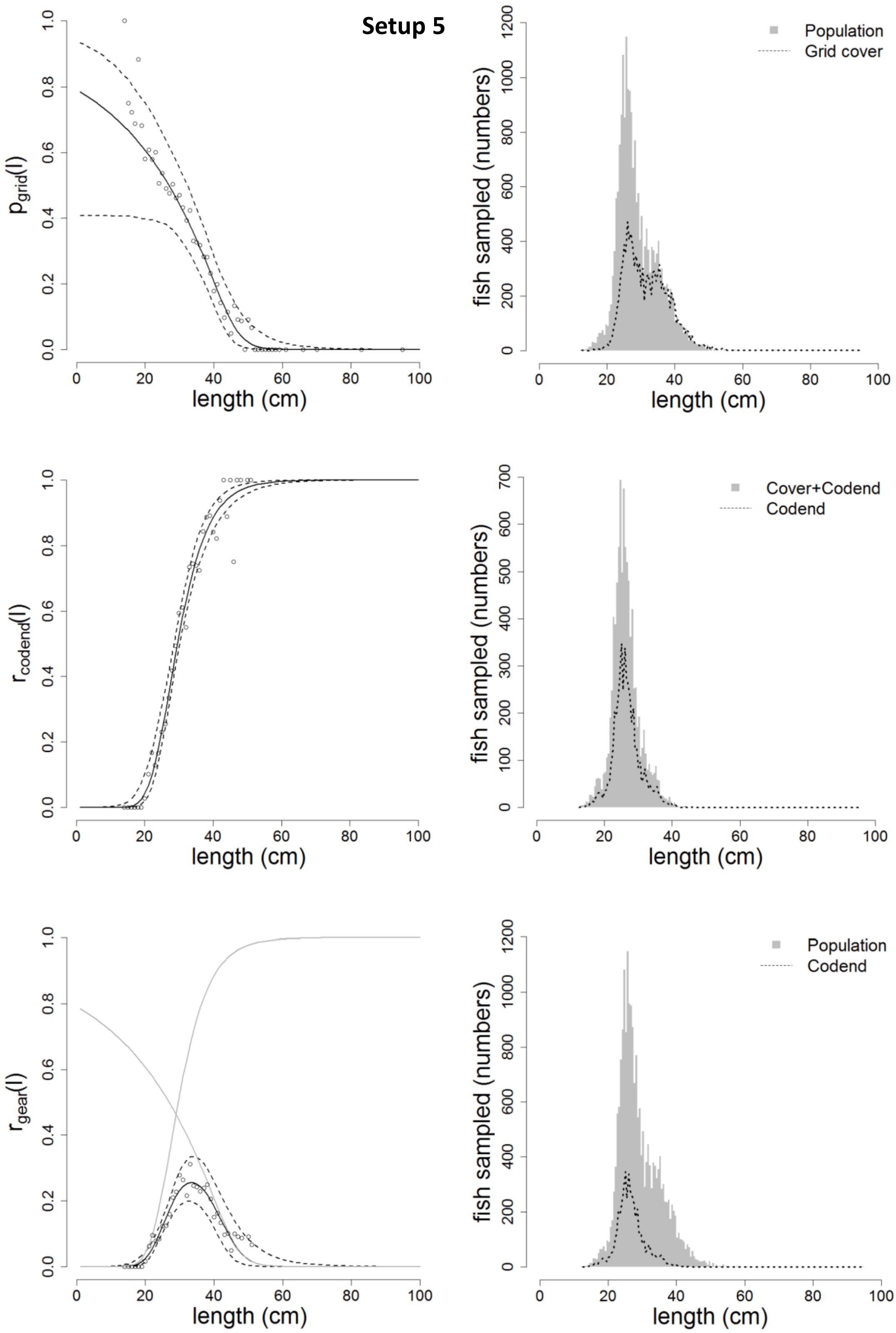

Figure 11: Setup 5 (42.5 mm bar spacing, 105 mm mesh size, without MEO); Left: Size selection curves of the different selection devices with 95% confidence Intervals (dots show experimental data, grey lines show selection curves of grid and codend). Right: Number of cod in the different compartments (dotted line: caught cod in the compartments, grey shaded area: number of cod entering the gear). Top: Selection of the 42.5 mm bar-spaced grid, without MEO. Middle: selection in the T90 105 mm codend. Below: Combined selection of grid and codend.

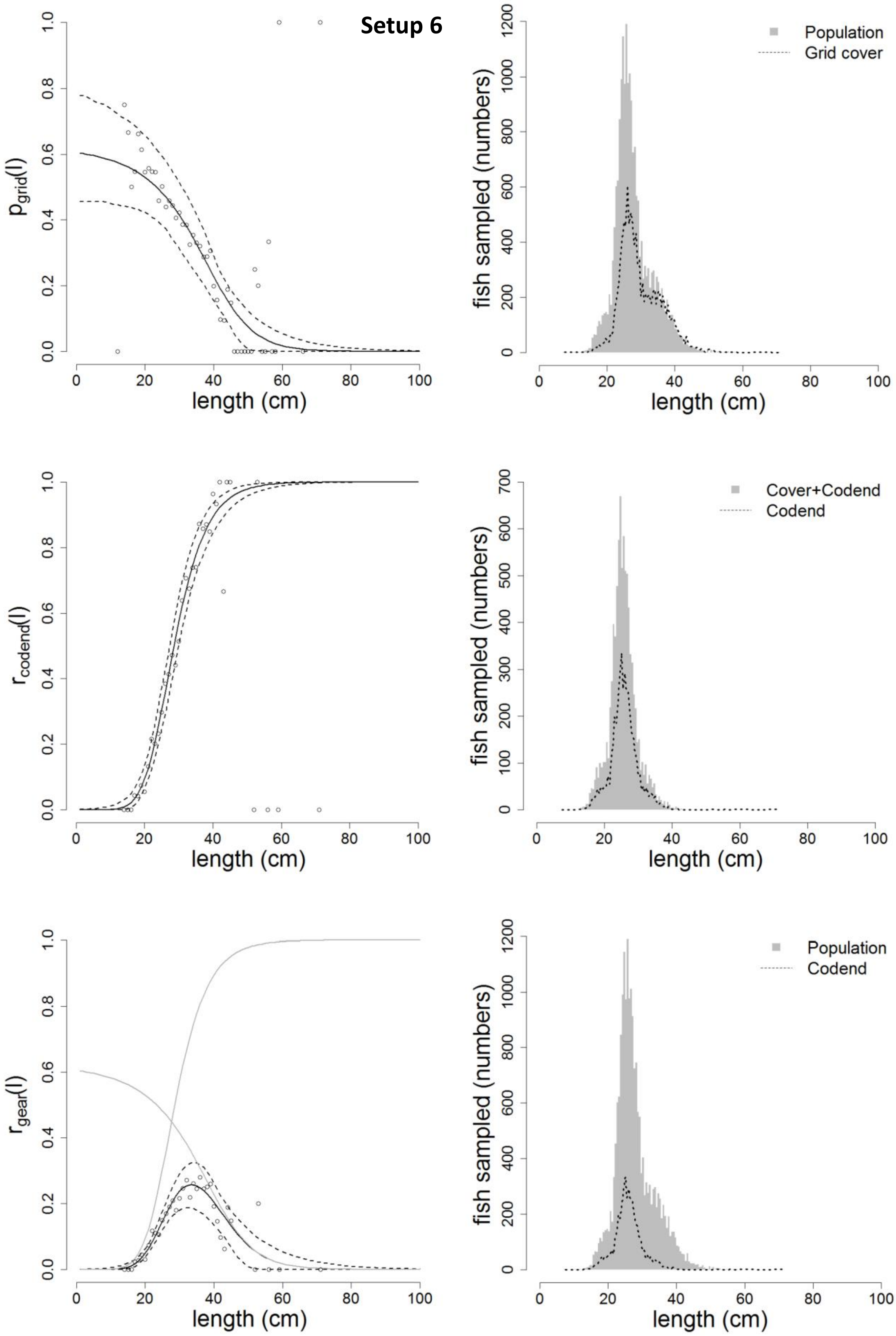

Figure 12: Setup 6 (42.5 mm bar spacing, 105 mm mesh size, with MEO); Left: Size selection curves of the different selection devices with 95% confidence Intervals (dots show experimental data, grey lines show selection curves of grid and codend). Right: Number of cod in the different compartments (dotted line: caught cod in the compartments, grey shaded area: number of cod entering the gear). Top: Selection of the 42.5 mm bar-spaced grid, with MEO. Middle: selection in the T90 106 mm codend. Below: Combined selection of grid and codend.

The selection curves of all setups show the partial S-shaped curves for grid and codend selection and bell-shaped curves for the combined selection, together with their respective bootstrap confidence intervals (Figure 8-12). The confidence intervals are in some cases considerable wide in the grid selection. Nevertheless, confidence intervals for the codend selection are relative narrow. Additionally, the population-plots give an overview, on how many cods are caught in the different compartments. Altogether, only few large cods were caught in every setup.

The selection curves of setup 1 (50 mm bar spacing, 120 mm mesh size, with MEO) represent the experimental data points well (Figure 8). However, data of larger length classes occurred only rarely. The confidence intervals are wider here. The graphic shows that the amount of small and large fish is reduced slightly by the selection devices. However, also many medium sized fish were able to escape from the trawl through the MEO. The maximum of the retention of the gear is approximately 40 % at a length of about 44 cm (Figure 8).

The experimental data of setup 2a (50 mm bar spacing, 105 mm mesh size, with MEO), which was conducted with a smaller meshed codend, were modelled well and the confidence intervals are narrower compared to the previous setup. Cods from every length class escaped through the escapement outlet but generally fewer small individuals. Again, also many medium sized cods were able to escape from the trawl. The maximum of the retention of the gear is about 60 % at a length of 40 cm (Figure 9).

The confidence intervals of the grid selection in setup 2b (50 mm bar spacing, 105 mm mesh size, with MEO) are considerable wide, especially in length classes above 40 cm. The number of large fish entering the trawl is very low. Although a few large cods passed through the grid and were caught in the codend, many large but also medium sized individuals escaped from the trawl through the EO and the codend. Mainly cods between 20 cm and 35 cm were retained in the codend (Figure 10).

In setup 5 (42.5 mm bar spacing, 105 mm mesh size, without MEO), almost all large cod left the gear through the EO. However, also many medium sized individuals escaped through the escapement outlet and the codend from the trawl. Again, compared to the length classes entering the trawl, mainly medium sized cods were retained in the codend (Figure 11).

The grid selection curve of setup 6 (42.5 mm bar spacing, 105 mm mesh size, with MEO) has wide confidence intervals in length classes up to 20 cm. A large proportion of the population, entering the trawl, was caught in the grid cover, including also many small individuals. Many cods between 25 cm and 35 cm escaped through the escapement outlet, partly more than 500 individuals in each 0.5 cm wide length class. Compared to the total amount of fish entering the trawl, only a small proportion of medium sized fish was caught in the codend (Figure 12).

The data analysis is focused on four aspects which arise from the different setups tested.

Effect of bar spacing (setup 2a vs. setup 6)

Comparing setup 2a (50 mm bar spacing) and setup 6 (42.5 mm bar spacing), c_{grid} shows higher mean values in the wider bar spacing (c_{grid}~0.73) than in the narrower (c_{grid}~0.62) (Table 7). This means that in setup 2a 73 % of all fish entering the trawl contacted the grid, whereas 27 % left the gear through the escapement outlet without contacting the grid and hence were not size selected by the selection devises. The model estimated significantly higher values for $L50_{grid}$ and SR_{grid} for setup 2a ($L50_{grid}$ ~47.9 %, SR_{grid}~8.2 %) than for setup 6 ($L50_{grid}$ ~35.8 %, SR_{grid}~17.6 %) (Table 7). Since the same codend was used in both setups, similar values for the parameters in the codend for setup 2a ($L50_{codend}$ ~29.8 %, SR_{codend}~11.1 %) and setup 6 ($L50_{codend}$ ~28.6 %, SR_{codend}~10.2 %) were estimated (Table 7). The amount of medium sized cod which escaped from the gear is significant higher in setup 6 (Figure 13).

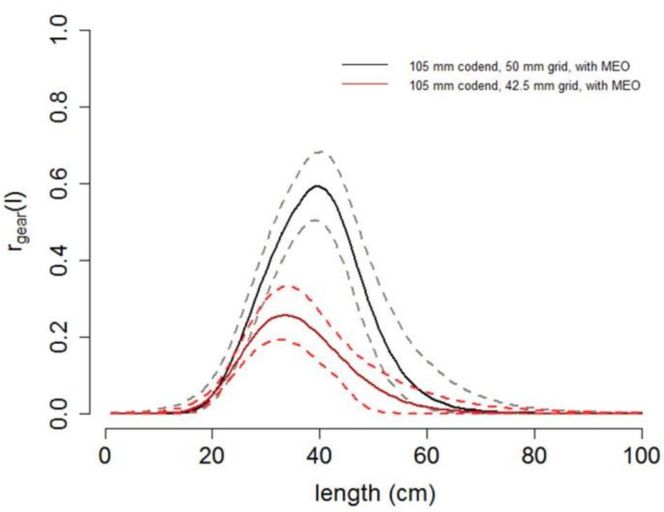

Figure 13: Comparison of the selection curves of setup 2a (black) and setup 6 (red) with confidence intervals

Effect of the MEO (setup 5 vs. setup 6)

While in setup 5 the net covering the escapement outlet above the grid (MEO) was removed, it was present in setup 6. The model estimated a grid contact probability of 94 % for setup 5, which is higher than setup 6 (62 %), but the confidence intervals were large and overlapped with the one in setup 6. The $L50_{grid}$ in setup 5 was smaller ($L50_{grid}$ ~28.51) but the SR_{grid} larger (SR_{grid}~27.81) compared to setup 6 ($L50_{grid}$~35.8, SR_{grid}~17.6). The parameters for the codends are comparable (Table 7). The setup with MEO catches a slightly higher amount of cod in length classes of about 50 cm (Figure 14).

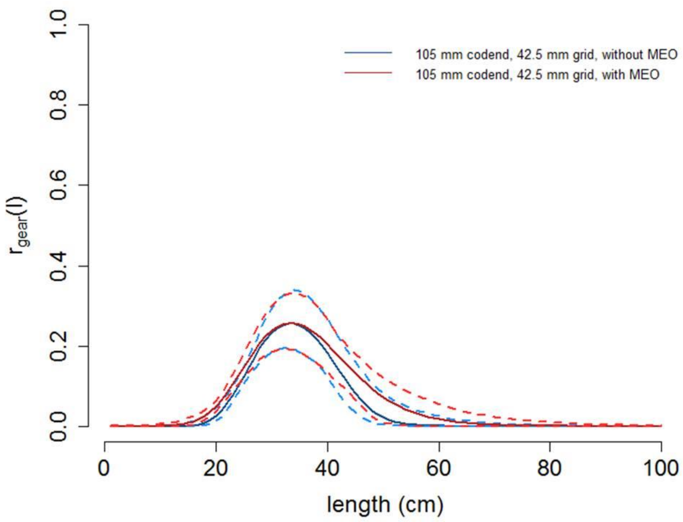

Figure 14: Comparison of the selection curves of setup 5 (blue) and setup 6 (red) with confidence intervals.

Effect of deformation of the grid (setup 2a vs. setup 2b)

In contrast to setup 2a, setup 2b showed deformation of the grid (Figure 20). The c_{grid} of setup 2b (63 %) was smaller than in setup 2a (73 %) but the confidence intervals overlap (Table 7). The L50 and SR of the grid were significantly higher in setup 2b ($L50_{grid}$ ~55 %, SR_{grid}~12.5 %) than in setup 2a ($L50_{grid}$ ~47.9 %, SR_{grid}~8.2 %). The parameters for the codend size selection are similar (setup 2a: $L50_{codend}$ ~29.8 %, SR_{codend}~11.1 %, setup 2b: $L50_{codend}$ ~30.32 %, SR_{codend}~10.14 %). Figure 15 shows that the catch of medium sized cod is slightly larger in setup 2a. Furthermore, the confidence interval in setup 2b is very wide and the amount of large fish is bigger.

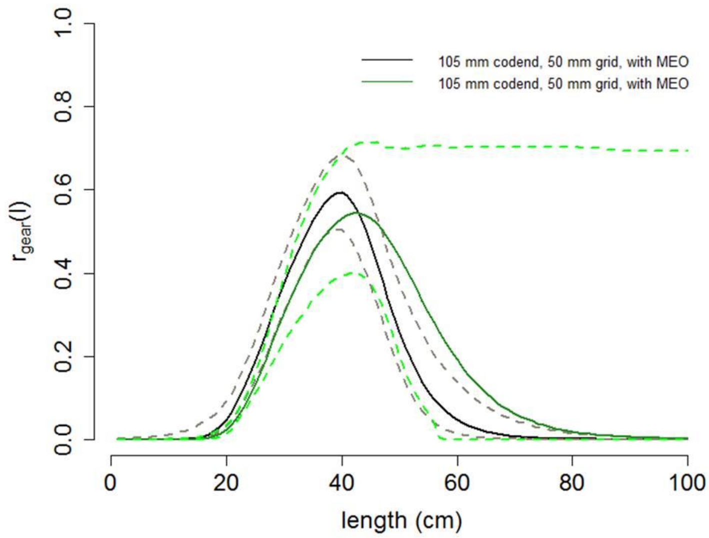

Figure 15: Comparison of the selection curves of setup 2a (black) and setup 2b (green) with confidence intervals.

Effect of the codend mesh size (setup 1 vs. setup 2a)

Whereas setup 1 used a 120 mm codend, all other setups used a 105 mm codend. However, only setup 2a is comparable to setup 1 since both differ only in mesh size. The grid selection parameters in setup 1 are slightly larger (c_{grid}~0.8, $L50_{grid}$ ~51.1, SR_{grid}~11.4 %) than in setup 2a (c_{grid}~0.73, $L50_{grid}$ ~47.9 %, SR_{grid}~8.2 %). The confidence intervals overlap each other. The mean value of the codend selection parameter $L50_{codend}$ is significant higher in setup 1 than in setup 2a. The value for $L50_{codend}$ is 42.0 and for SR_{codend} 12.0 in setup 1 (setup 2a: $L50_{codend}$ ~29.8 %, SR_{codend}~11.1 %) (Table 7). The number of small fish in the codend is significant larger in setup 2a (Figure 16). The probability that a cod of medium length classes is caught in the codend is significant higher in setup 2a than 1 (Figure 16).

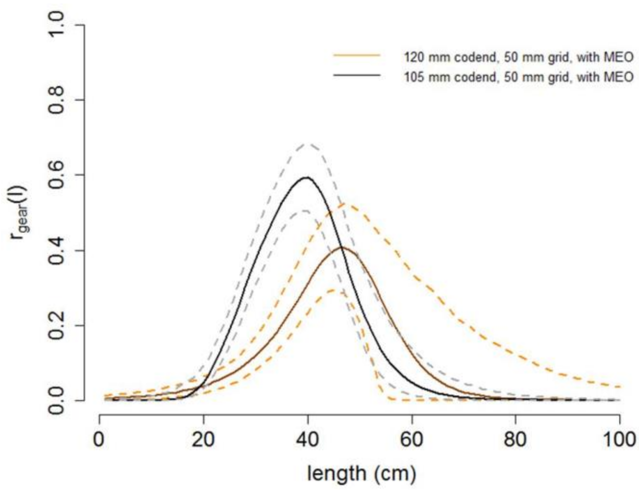

Figure 16: Comparison of the selection curves of setup 1 (brown) and setup 2a (black) with confidence intervals.

3.5 Underwater video

Altogether, 41 underwater videos with a total duration of 26.5 hours were collected in 36 hauls. Since the cameras do not use artificial light, it was not possible to use them in all hauls or during the entire haul. The video recording quality for hauls performed on deep fishing grounds was poor. Those videos were not used in the qualitative analyses.

Using the underwater videos it was possible to observe a different behavior of roundfish and flatfish. Roundfish, and especially cod, tried to keep clear of the netting during the whole towing process and also avoided contact with the grid (Figure 17). After a few minutes, the cod were exhausted and stopped swimming and were pressed against the grid. On the contrary, flatfish kept in contact with the lower net panel during the whole towing process. The videos showed that flatfish often stopped swimming and lay on the lower panel. If an obstacle, in this case the grid, occurred, they were pressed against it but did not try actively to fit through the bars since they did not alter their swimming direction.

Figure 17: Screenshot of an underwater-video recording. The camera is pointed in the direction of the codend. Cod swim freely in the water column, whereas flatfish keep in contact with the lower net panel (setup 2a, haul 23)

It is noticeable that during heaving especially cod tried to swim vertically to the lower part of the net and even touched it there (Figure 18). Flatfish did not show this behavior.

Figure 18: Screenshot of an underwater-video recording. The camera points from the trawl belly to the grid. Cod swim vertically to the lower part of the trawl (setup 5, haul 37, during heaving).

Additionally, there are two noteworthy aspects in relation with the grid: blocking and deformation. The effect of blocking in front of the grid occurred with the 50 mm, as well as with 42.5 mm bar spacing. Fish, mainly flatfish, organic debris (i.e. pieces of algae) and litter accumulated in front of the grid and reduced the area available for mechanical fish sorting, sometimes significantly (Figure 19). In the other hand, deformation of the grid was first detected in the underwater videos in setup 3. However, it was later detected that it also occurred to a greater extent in setup 2b. As shown in Figure 19, the bars are bended and therefore the bar spacings vary in width by several centimeter. The grid in total showed a concave shape.

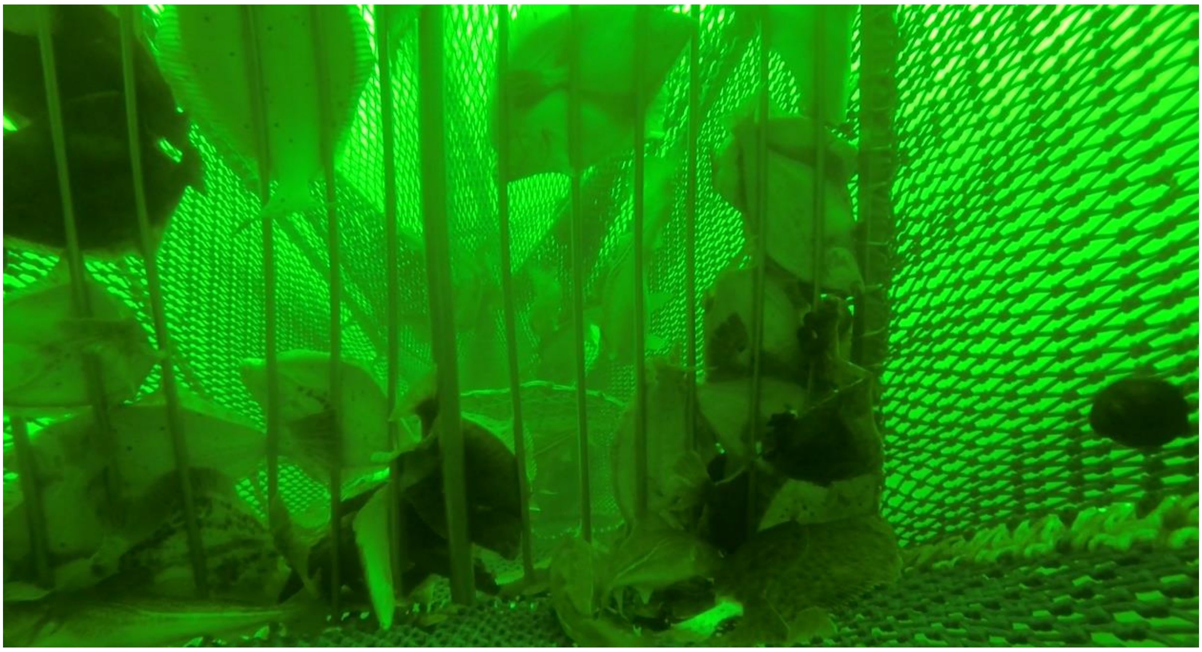

Figure 19: Screenshot of an underwater-video. The camera points from the codend to the grid. Flatfish accumulate in front of the grid (setup 2b, haul 33). Grid deformation is visible.

4. Discussion

4.1 New exploitation pattern

Aim of this study was to investigate a new selectivity concept, which not only focuses on the protection of small but also of large fish. Therefore, the concept is different to the traditional exploitation pattern in trawl fisheries. Large fish are very important for the fish stock, since they produce more eggs with a higher quality than smaller individuals (Birkeland and Dayton, 2005). By using the new gear technology, it is the aim to achieve small catching rates in small and large length classes. In contrast to the traditional S-shaped selectivity curves, the result is now a bell-shaped selectivity curve with the highest catching rates for medium sized fish.

Two well-known selectivity devices were combined in the experimental gear presented here: a grid and a codend. Adopted and adapted from the nephrops fishery (Catchpole and Revill, 2007), a grid was mounted in the tunnel, the piece of net connecting the cone-shaped gear body to the codend. This grid only allowed small and medium sized individuals to enter the codend, since large fish do not fit through the bars. They can leave the trawl through an outlet above the grid. Since the selection of large fish already takes place before entering the codend, it is assumed that they are affected very little. Small fish escape from the trawl in the codend, where meshes are used, which were rotated by 90° and stay relative open during towing. Medium sized fish is retained in the codend. This concept is new for the target species and was tested in the cod-directed fishery in the Baltic Sea.

In order to find a configuration in which grid, escapement outlet and codend work well together, seven different setups were tested. Some of the defined setup could not be used in the later statistical analysis of the data, due to practical problems which produced a sub-optimal performance during fishing or due to confounding effects. For example, the underwater videos showed that reducing the grid angle from 75° to 45° results in a reduced tunnel height. This significant reduction might produce a confounding effect that could make it impossible to assess the effect of reducing the angle of attack of the grid as a separate effect. Nevertheless, it was possible to estimate the model for five setups and obtained well-defined bell-shape selectivity curves in those cases.

4.2 The grid

The analyzed data allow the comparison of three grid configurations, potentially affecting the grid performance.

Effect of bar spacing (setup 2a vs. setup 6)

The reduced bar spacing (42.5 mm) in setup 6 lead to a reduced contact probability of cod with the grid, in contrast to setup 2a which had the wider bar spacing (50 mm). Cod, once entered the net, tries to avoid any contact with the net. A narrow bar spacing might increase the wall-effect. Many cod try to avoid the grid and therefore do not try to pass through it. The wider bar spacing allows larger fish with a larger girth to pass through the bars. Therefore, the wider bar spaces resulted in a significantly higher $L50_{grid}$ so that in average larger fish were caught in the codend. Additionally, the 50 mm bar spacing had a smaller SR_{grid}, which means that the selectivity is sharper and the curves are steeper. This might result from the fact that the fish tries actively to swim through the grid because the contact probability is almost 10 % larger in setup 2a than in setup 6. Compared with the length distribution of cod entering the trawl, these values show that the selection of the grid works well. The length of cod entering the codend depends significantly on the bar spacing.

Effect of the MEO (setup 5 vs. setup 6)

Setup 5 and 6 only differ in the presence of the MEO. It was installed to make the EO less visible for fish and to prevent them to leave the trawl through the outlet without previously contacting the grid. Therefore, it was intended to improve the contact probability of the grid. Comparing c_{grid} of setup 5 and 6, there is a trend of the mean value that more fish contacted the grid without the masking panel. Since the confidence intervals from both estimations overlap, the differences are not statistically significant. This means that the MEO did not improve the selection of the gear and might even worsened it. Additionally, c_{grid} is not only depended on the absence and presence of the escapement outlet but also of the number of fish entering the trawl at once and the area of attack (AA) (Sistiaga et al., 2010). As seen in the videos, the AA is reduced by macro algae, flatfish and also litter. Table 4 also shows that the number of fish entering the trawl varied greatly between the hauls. All these uncontrolled effects are absorbed by the uncertainty estimated by the bootstrap scheme applied in the inference, explaining the width confidence intervals associated to the estimated curves. The significance of the data might be increased with a higher number of valid hauls.

Effect of deformation (setup 2a vs. 2b and 5 vs 6)

The grid deformed heavily during the sea trials. Although it was made of steel, the pressure of the net, when it was winded on the winch, altered shape and bar spacing (Figure 19 and 20). Since the grid did not show any deformation in setup 2a but in 2b, those two setups can be compared. Setup 2b shows higher values of $L50_{grid}$ and SR_{grid}. The bar spacing in setup 2b changed irregularly due to deformation, so that some bar spaces were smaller than 50 mm and some were larger. Dependent on where the cod contacts the grid, the probability to pass through is different. This explains the higher SR_{grid}. Since the $L50_{grid}$ of setup 2b is larger, it can be assumed that some bar spacing were significantly larger (compare Figure 19 and 20). The 42.5 mm grid, used in setup 5 and 6 changed its shape slightly, although not as much as the other one. There is still a higher $L50_{grid}$ in setup 6 than in setup 5, which was conducted before deformation was first observed. This might also be the result of the presence and absence of MEO, the aspect in which those two setups differ. The bar spacing in setup 5 and 6 is smaller and therefore has two additional bars. The grid seems to be more stable. However, it has to be thought about a new material or grid concept, which performs stable under water but is flexible on the winch.

Figure 20: Photography of the 42.5 mm steel grid with deformation of shape and bar spaces (A: frontal, B: lateral).

As presented in the Figures 8-12, too many medium sized and small fish escaped through the EO without being size selected by the grid. To improve this aspect, the c_{grid} needs to be further improved. For example, the structure of the guiding panel can be adapted so that more cods contact the grid and try actively to pass through it.

4.3 The codend

Currently, codends with a mesh size of 120 mm are standardly used in the cod directed fishery in the Baltic Sea. For the specific objective of the present study it was more important to focus on the selection process of the grid and the interaction of grid and codend selection. The mesh size in the codend has significant influence on the length dependent catchability of cod. Comparing the $L50_{codend}$ values of setup 1 (120 mm mesh size) with the other four setups, which used a smaller meshed codend (105 mm mesh size), the value was significantly higher in setup 1. The selectivity parameters $L50_{codend}$ and SR_{codend} of the setups using 105 mm mesh size were all relative similar. Also setup 2a which, compared to setup 1, only varied in mesh size, has a larger mean value for $L50_{codend}$. The value was more than 10 cm higher in the larger meshed codend. The experiment showed that the selection of fish due to altered mesh sizes works well. However, as stated in Glass (2000) the codend design is more important in the selectivity of trawls than the mesh size. Nevertheless, Glass starts from the premise that it is a diamond mesh and not a T90 mesh, which is kept open even at high pressures due to high catches. Since already T90 meshes were used in the codend, the increased mesh size had a significant influence on the L50.

4.4 Fish behavior

The underwater-videos illustrate clearly that the behavior of roundfish, in this case cod, and flatfish, in this case flounder, plaice, turbot and dab, differ fundamentally. Fish which enter the demersal trawl react to the gear and are not caught passively (Main and Sangster, 1981). While cod avoid contact with the netting, flatfish swim along the lower net panel. This behavior can be explained with their different anti-predator-behaviors and is similar to what Ryer (2008) observed. He outlines that roundfish can appreciate their predators in great distances and try to avoid them. That is why they keep clear of the netting. By contrast, flatfish normally live on sandy seafloor. Due to their color and shape they are hard to see. When detecting a danger, flatfish burry in sand. Only if the predator gets very close, they flee (Ryer, 2008). This explains why flatfish, as seen in the underwater observations, lie on the lower net panel and only swim occasionally. Furthermore, flatfish only show fleeing behavior for several seconds before they lay again on the net. In contrast, cod is more persistant. They swim with a gear which is towed with 1.5 m s^{-1} up to two minutes before they fall back into the codend (Main and Sangster, 1981; Ryer, 2008) or in this case an obstacle, the grid. Only if they touch the grid they attempt to swim through it or are pressed through it (if they fit through) or against it (otherwise) by the water current.

Since the natural swimming direction of flatfish is contrary to the orientation of the grid, flatfish with a wider body than the bar spacing do not fit through the bars and are pressed against it. They do not try to pass through them actively. While they are pressed against the bars, caused by the waterflow, they prevent other fish to pass through the bars. If the water flow or other entering fish move the flatfish and change their orientation, they might be pressed through the grids and enter the codend. However, the meshes in the codend are developed to reduce the amount of undersized roundfish. Again, flatfish cannot pass through the meshes and block them. Depended on the amount of flatfish they can prevent small roundfish from escaping the codend. Both flatfish and small roundfish often suffer physiological trauma und stress, even if they finally escape from the trawl (Ryer, 2008; Sangster et al., 1996).

The underwater-videos also show that cod altered their swimming direction during heaving into a vertical position and even touched the lower net panels. Knowing that cod normally avoids any contact with the gear, underlines this unusual behavior. Many bony fish use a swim bladder to regulate the amount of gas in the body and to allow floating in the water. In contrast to physostomes, which can regulate the volume of the swim bladder through the intestinal tract, physoclists, like cod, have a closed swim bladder. They regulate the volume by absorbing gas into or out of the bloodstream upon a membrane (Figure 21) (Midtvedt et al., 2007). This process might not be as fast as the trawl is heaved because the air volume in the swim bladder increases rapidly while moving to shallower waters due to a decrease of water preassure. The cods try to compensate this difference in pressure and swim into deeper water but are stopped by the net. Since flatfish are exclusively demersal fish, they do not need a swim bladder at all. It is formed back after leaving the larval stadium to save energy (Kapoor and Khanna, 2004). That is why the videos do not show a downwards swimming behavior of flatfish during heaving.

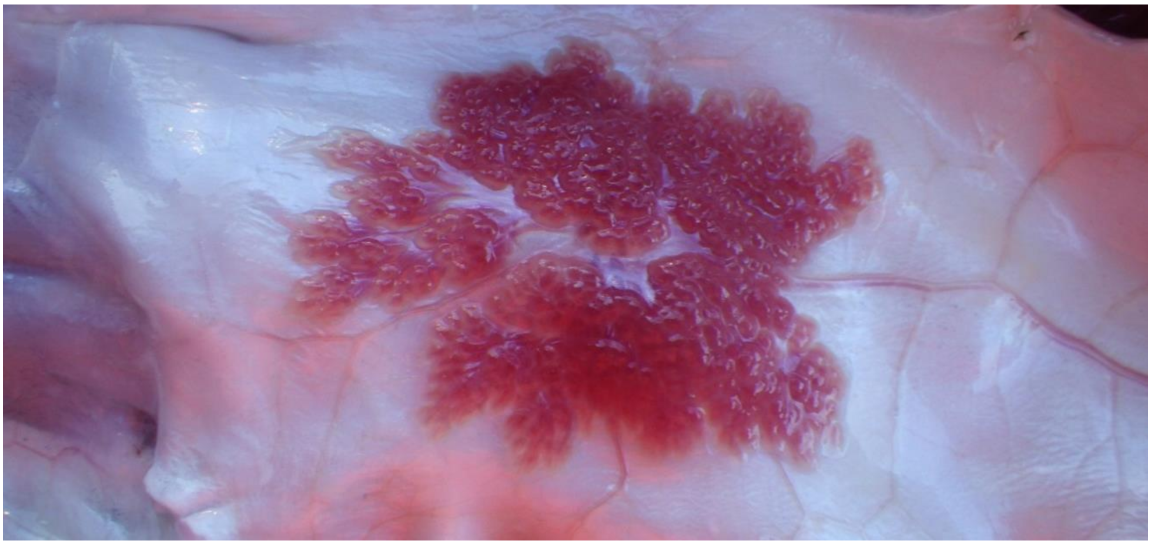

Figure 21: Photography of the membrane (Rete mirabile) with which the cod conducts the gas exchange in the swim bladder.

4.5 Conclusion

This study showed that it is possible to obtain a completely different exploitation pattern compared to the commonly known size selection of trawl. Due to the different settings of the grid and the codend it was possible to alter the length distribution in the codend. Especially changes in the codend mesh size and the bar spacing showed significant results. Nevertheless, the influence of the net panel to cover the escapement outlet seems minor. Due to a reduced tunnel height, grid angles of 45° are not useful. The results point out clearly that the contact probability of the grid has to be further improved to avoid the loss of wanted fish. It should be noted that the resulting overall selection improves when the selection curves of grid and codend are more divergent. However, this was not possible in the experimental setups since the length distribution of cod was very narrow at the moment of testing and the proportional of large cod was very small. Additionally, underwater observation showed that cod avoid contacting the grid. Furthermore, since the grid showed already deformation after a few hauls, a more appropriate grid construction has to be found. This experiment was an important step to show that different, potentially more sustainable exploitation patterns are possible. Now this new gear has to be improved to allow a practical use in fisheries.

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Acknowledgements

Special thanks to Juan Santos for his huge support during the preparation of this thesis. He not only taught me the whole statistics I needed but also gave many suggestions and improvements for my writing, even when he was on holidays. I would also like to thank Dr. Daniel Stepputtis for his permanent support in every scientific situation from preparing a poster over writing my thesis to many useful contacts. Both of you taught me more practical skills than 2.5 years of study and it is always a pleasure to be with you on SOLEA. Thanks also to Annemarie Schütz and Bernd Mieske for nice talks and supports in the institute. Thanks to Prof. Dr. Peter Schupp and Dr. Sven Rohde, who enabled that I can finally write about my favorite topic.

Many hugs to my private supporters: My family and Björn but also my friends from home, Oldenburg and Rostock, who made this summer unforgettable.

Appendix

List of Abbreviations

AA: are of attack of the grid

AIC-value: Akaike Information Criterion, used for model selection

CC: Codend Cover

CD: Codend

c_{grid}: probability that a fish contact the grid

DOF: degree of freedom

EO: escapement outlet

FAO: Food and Agriculture Organization of the United Nations

GC: Grid Cover

ICES SD: ICES subdivision

ICES: International Council for the Exploration of the Sea

L25: Length, at which 25 % of the fish is retained

L50: Length, at which 50 % of the fish is retained

L75: Length, at which 75 % of the fish is retained

MEO: masked escapement outlet

MLS: Minimum Landing Size

p_{grid}: passing through probability of the grid

r_{codend}: retention probability of the codend

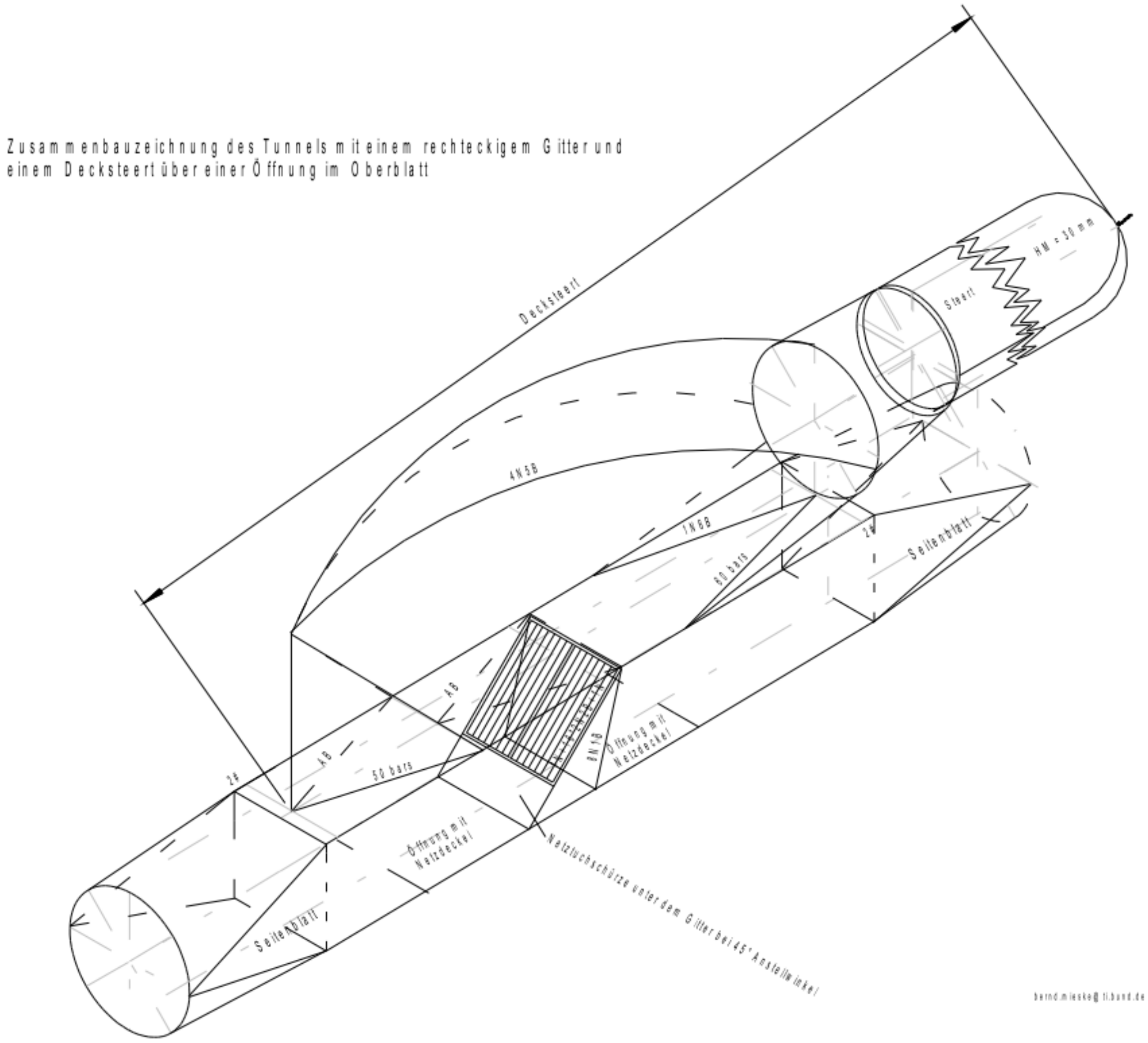
r_{gear}: retention probability of the gear

SR: Difference between L25 and L75

T90: meshes are turned through 90 °

UW: Underwater

Technical drawing



Appendix Figure 1: Technical drawing of the tunnel with grid and grid cover over the escapement outlet

Pictures

Appendix Figure 2: The codend is heaved onboard.

Appendix Figure 3: Cod on an electronic measure board.

Selbstständigkeitserklärung

Hiermit versichere ich, dass ich diese Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Außerdem versichere ich, dass ich die allgemeinen Prinzipien wissenschaftlicher Arbeit und Veröffentlichung, wie sie in den Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg festgelegt sind, befolgt habe.

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