European Commission

Collaboration between the scientific community and the fishing sector to minimize discards in the Baltic cod fisheries

Full Study Report

Submitted by

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The study and report have been prepared with the financial support of the European Commission. Their aim is to provide information and analysis on different aspects of the Common Fisheries Policy and to feed into discussion on these issues.

Executive summary

Background

The Council of the European Union and the European Commission agreed at the 2009 October Fisheries Council to develop a roadmap to eradicate discards in the Baltic Sea. On the 11th of June in 2013, political agreement was reached on a new common fishery policy (CFP), with an implementation of a discard ban as one of the major changes. This discard ban will be implemented into the Baltic cod fishery in 2015.

Cod fisheries in the Baltic Sea date back a long way, although more intensive exploitation only occurs since the 1950s. The cod fishery was further intensified in the 1980s when the stock biomass substantially increased due to favourable reproductive conditions resulting in a number of strong year classes. Today, bottom trawling is the predominant fishing method in the fishery while earlier hooks and gillnets dominated. The Baltic Sea trawling fleet catches the major fraction of the discarded cod. Additionally, this fishery is known to have significant, but highly variable, discard rates of flatfish species such as flounder and plaice.

Technical conservation measures also have a long history and were first governed by the International Baltic Sea Fishery Commission (IBSFC) before most Baltic countries became EU members. Gear regulations for cod trawls in the Baltic have changed many times during the last 20 years and are now mainly gathered in EC Council regulation 2187/2005. Amongst others, this regulation defines codends to be used in the Baltic trawl fishery targeting groundfish species. Thereby two codend designs are legalized, the Bacoma-codend with a 120 mm square mesh escape window, and the T90-codend with 120 mm diamond mesh netting which is turned 90°.

Objectives and scope

The main aim of this study was to identify technical solutions, both economically and biologically sustainable, to mitigate the discards of cod in the Baltic Sea cod fishery. The aim of the project was divided into three main tasks:

- Assessing the present knowledge on discards and causes of discards in the Baltic cod fishery, and exploring the temporal and spatial distribution patterns of discard sensitive size classes of cod and of the fishery effort.
- Identifying technical solutions and suggesting final technical measures to further mitigate discards in the trawl fishery for Baltic Sea cod.
- Evaluating the possible impacts of the proposed technical solutions and technical measures on the stock and on the economy of the fisheries concerned.

These tasks were undertaken through a desktop study, a technical study and an impact study.

In order to engage trawl fishermen in the project, a questionnaire was sent in spring 2012 to active fishermen in Sweden, Denmark, Germany and Poland. The aim was to establish a dialogue with the industry on selectivity, gear selection, discard patterns and management options, and to collect their views, problems and potential solutions to mitigate discards. This questionnaire was the basis for further discussions with the industry during a workshop.

Desktop study

Discard in the Baltic Sea trawl fisheries targeting cod

The Baltic Sea cod trawl fisheries have been systematically sampled for discards since the mid-1990s. Since 2002, sampling is carried out according to EC data regulations.

The discard fraction of the catch is dominated by a few species. In the eastern Baltic, 25 species were found in the discards, of which cod, flounder and plaice constituted 99.5% of the overall catch weight. In the western Baltic (subdivisions 22 and 24), dab and whiting are common as well. In total, 52 species were found in discards (Figure I).

The total amount of discards varied between 0 and 4.7 tonnes with a mean of 224 kg per haul. The amount of cod discard varied between 0 and 3.3 tonnes with a mean of 127 kg, resulting in a mean discard rate for cod of 10 % in weight. This discard rate of cod varies considerably between hauls, but also between years and countries. Differences between countries are also reflected in the responses in the questionnaire survey, which was conducted with the industry. A larger proportion of the Swedish fishermen have answered that they have higher discard rates (> 10% and higher) compared to the other participating countries Denmark, Germany and Poland. The overall mean, 10 %, is in the top end of what the majority of the fishermen, based on the questionnaire survey, found to be an acceptable level of discard.

The vast majority (95 %) of the cod discarded during the observer trips between 2002 and 2010 are at or below minimum landing size (MLS). About 83 % of the discarded cod were between 30 and 37 cm in both number and weight. 90 % of the discarded flounder and plaice are above MLS, indicating that market consideration (low price) is a major reason for discarding flounder and plaice.

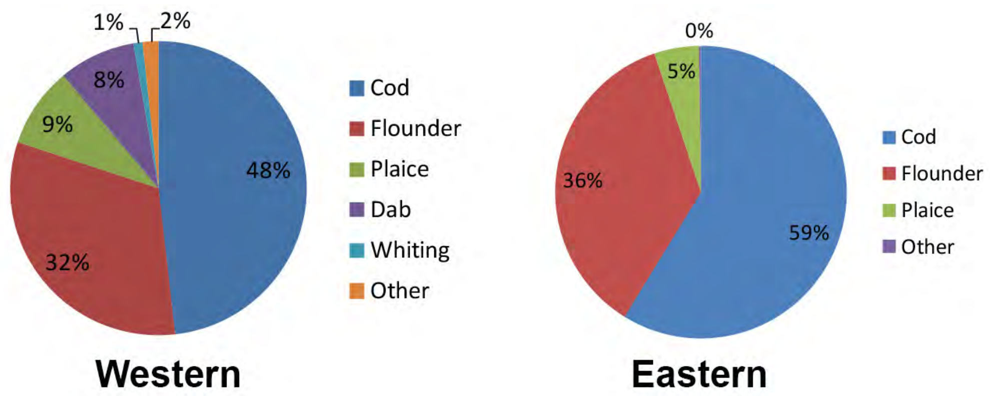


Figure I. Species composition in discard in eastern and western Baltic trawl fisheries.

Total catch size, the bycatch of flounder and vessel size have been suggested to have an impact on discard rates of cod in the Baltic Sea cod fishery. From the observer data this pattern was not clear, except for catches above 1500 kg of flounder, which increases the discard rate of cod to about 17 % on average. Therefore, the (often unwanted) catch of flatfish also influences the discard rate for cod.

Modelling the spatial and temporal distribution of Baltic cod and trawl fishery effort to evaluate hot-spots as potential area closures to reduce discards

Obvious methods to reduce discards are either to diminish the total fishing effort or to introduce more selective gears. Closed areas, both permanent and temporal, are potentially useful management measures if aggregations of discard sensitive species or size-groups exist and can be identified. The disadvantage, however is that the simultaneous reduction in catch per unit effort generally results in a loss to the fishermen in the short term. A crucial challenge for the managers is thus to minimize this loss in the short term, while still achieving the management goals set-up in the long term. In the present study, we analysed the spatial distribution of cod and the cod trawl fishery exploiting Western and Eastern Baltic Sea cod stocks to predict the efficiency of area closures to protect juvenile cod and the impact of these closures on the activity of the trawl fishery.

The analysis is composed by the following parts:

- Modelling the spatial distribution of three different size classes of cod (30-37, 38-48 and >48 cm).
- Estimate hotspot areas of discard sensitive size classes of cod. Hotspots areas were identified using three arbitrary global thresholds of 25%, 50% and 75%. In practice, these target levels aim to identify those areas with the highest concentration of discard sensitive cod. These areas include each season and year 25%, 50% and 75% of all the estimated number of discard sensitive size groups of cod (30-37 cm).
- Estimate the temporal stability of these hotspot areas by calculating the persistence index. We then calculate a polygon around those areas/grid cells selected as hotspots for at least 11 times over the 22 time steps (2 quarters x 11 years) used in the analysis.
- Overlay analysis of the persistence of hotspot areas of discard sensitive (30-37cm) and commercial size classes of cod (38-48 and >48cm).
- Overlay analysis of the persistence of hotspot areas of discard sensitive classes of cod (30-37 cm), the fishing effort and catch distributions of the commercial trawl fleet in the Baltic Sea.

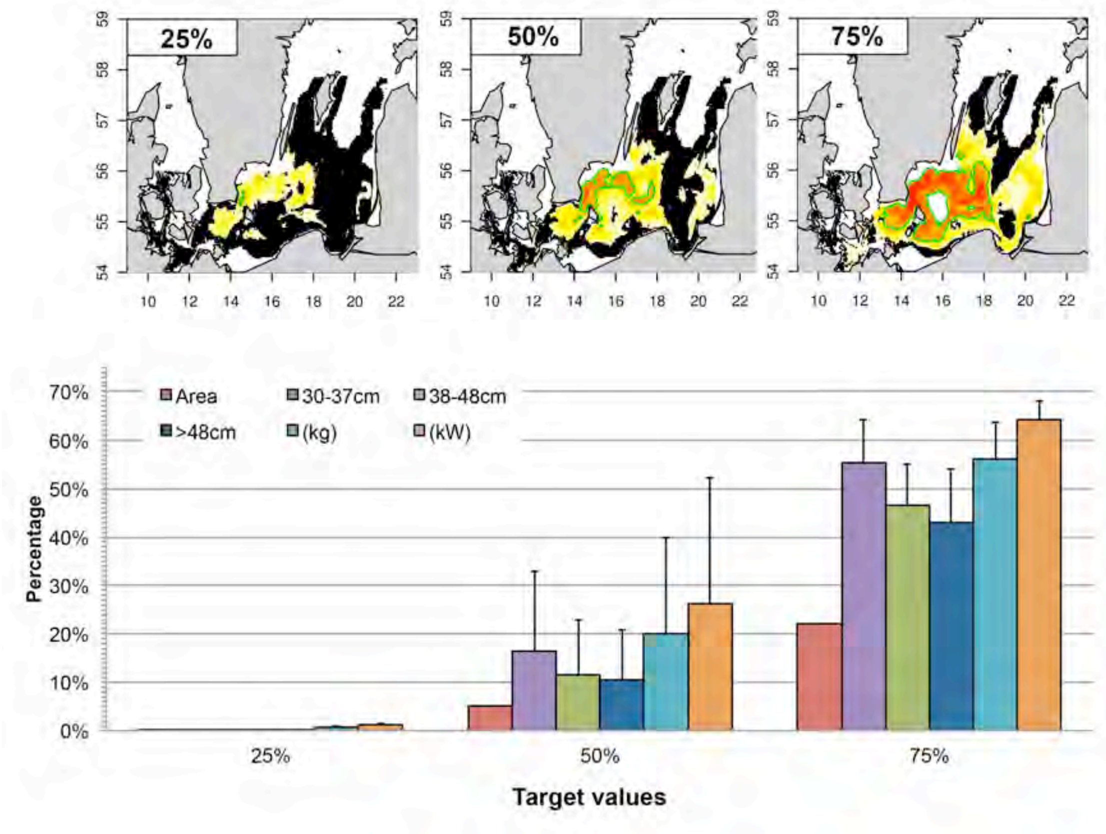


Figure II. Overlay analyse of the different size classes of cod (30-37, 38-47 and >48cm) and the fishery (landings [kg] and effort [kW]) in the persistent hot-spot areas between 2005 and 2010. Maps are showing the results of the persistence analysis, with the green polygons outlining areas potentially candidating for closure. The diagram is showing the relative size of the persistent hotspot areas, the average fraction over time of cod in each size class (30-37, 38-48 and >48cm) and fishery (mean landings [kg] and effort [kW]) of the total estimated distribution between 2005 and 2010, and standard deviation.

Overlay analysis of the different scenarios shows very low efficiency in protecting cod, less than 1 % in numbers of discard sensitive cod protected, using a management target of 25 % (the persistent hotspot area representing 25 % of the discard sensitive size classes of cod at least half of the times, between 2001 to 2011, quarter 1 and 4, respectively) for persistent hot-spots (Figure II). Using levels of 50 and 75 % increased the efficiency significantly to 15 and 57 % in numbers of discard sensitive cod protected.

We conclude that the modelling approach allows us to predict hotspots and areas with regular occurrences of different size classes of cod, based on scientific survey results. However, the overlay analysis of potential closures with distribution of commercial size classes of cod, fishing effort and landings conflict significantly with persistent hotspot areas indicating that closing these hot-spots will redistribute and increase fishing effort for cod in nearby areas if quotas of total allowable catch (TACs) are maintained.

Technical study

The central part of the project was the identification of potential gear designs, as well as testing and improving the selected designs. This included the following steps:

1. Technical review of gear changes in the Baltic Sea, its implication on selectivity and the current knowledge of trawl gears and selectivity in the Baltic Sea.
2. Discussion of current status, needs, ideas and future steps with the industry, including
   a. questionnaire survey among the fishery, as a basis for further discussions
   b. workshop to further discuss the needs of the fishery and to propose and identify potential solutions to be tested within the project
3. Test and improvement of proposed technical designs

A technical review was conducted based on available literature. There have been several changes of technical measures, affecting the trawl fishery for Baltic cod, during the last years. The resulting change in size selectivity of cod is illustrated in Figure III, also indicating the relative good selectivity of the current legal codend-designs [BACOMA 120 mm (incl. a 120 mm square mesh netting) and T90 120 mm (120 mm standard diamond mesh netting turned by 90°)].

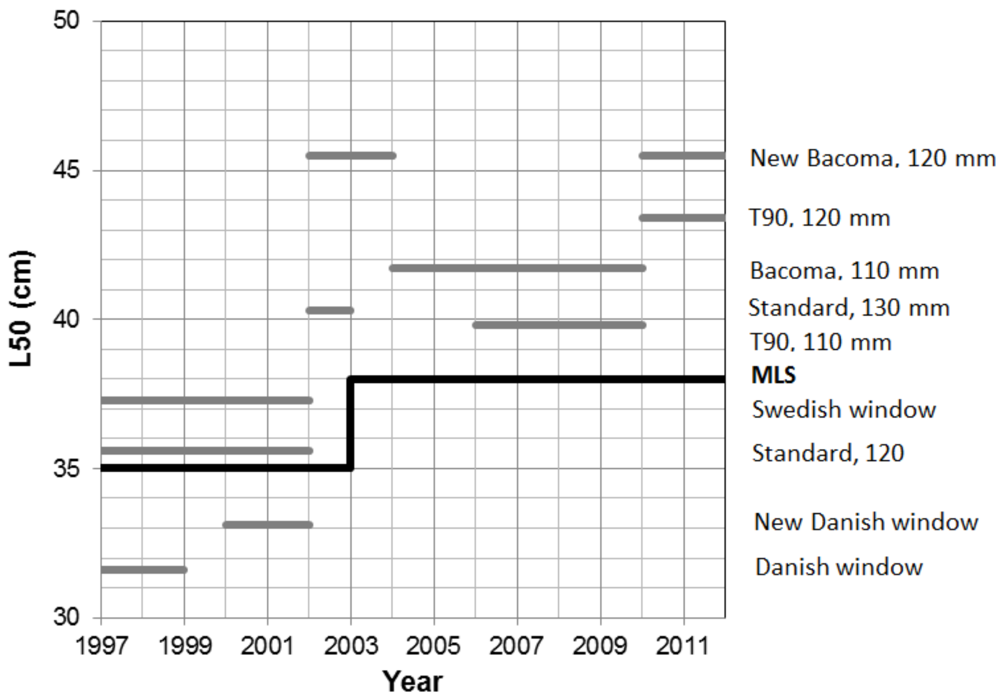
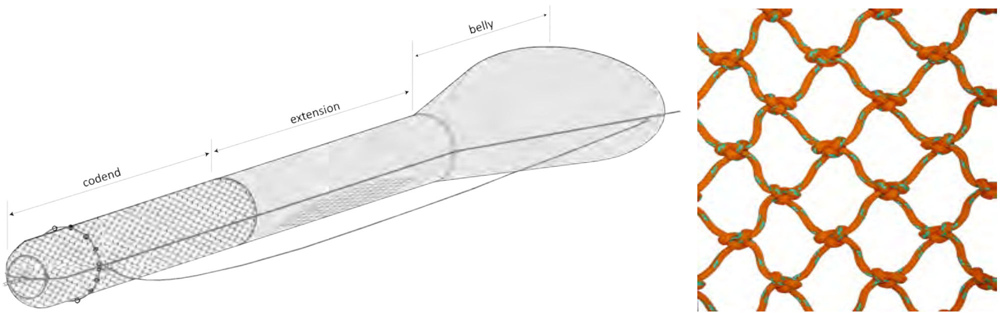


Figure III. Schematic presentation of changes in codend selectivity (L50) and in Minimum Landing Size (MLS) relevant for trawl fishery targeting Baltic cod. L50 indicates the length of an individual that has a 50 % probability of being retained after entering the codend. Figure is modified from Feekings et al. (2013).

Based on the technical review and the discussions with the industry, several problems and their potential solutions were discussed. The following summary pages give an overview about the final four gear modifications which were further developed within the project and tested during sea trials on commercial vessels.

Initial research vessels trials were also carried out on the full range of technical solutions proposed during the discussions with the industry, although the limited budget forced to choose a reduced number of technical solutions to be tested in commercial fishing trips, and the selection criteria was based on the results obtained during the first experimental phase mentioned above. Finally, only the so-called "envelope codend" solution proposed by the industry was left out from the final commercial tests. Brief descriptions of the tested solutions are showed below together with the results from their experimental test in commercial conditions:

Suggested gear 1: T90 s8



Left: Schematic drawing of tested T90 s8-codend (T90 codend with 8 mm single twine); Right: detail of netting used in T90 s8 codend

problem to solve/rationale

Based on the current legislation, the diamond mesh netting used in the T90- and the lower panel of the Bacoma- codend can be made using different twine characteristics (single twine up to 6 mm or double twine up to 4 mm). The twine characteristic is assumed to have an influence on the selectivity. Improved knowledge about the influence of twine properties is therefore necessary to optimize the size selection of codends in the Baltic Sea.

science – fishery discussions

- problem: discussed during the workshop in 2012
- solution: development of a T90 codend made of diamond netting with twine characteristics that results in a clearly defined/more stable selectivity and sharper selection curve (small selection range)
- rationale:
  - improving selectivity for cod

gear developed and tested

A T90 codend was constructed using single twine with 8mm twine thickness (T90 s8) with a nominal mesh size of 120 mm. This decision was made after analysing experimental data from a research cruise, investigating the influence of the number of twines and twine thickness on the size selectivity for cod (Annex IV). The tested codend was a 2 panel-construction.

Pros: cheap to build and easy to use   Cons: single twine with 8mm is not in legislation today

tests and experiments

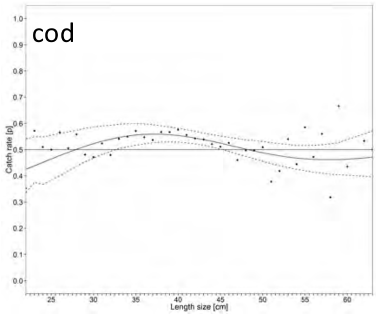
A) sea trial onboard FV “Veronica of Fiskebäck” GG352 (SE)

when: March/April 2013; where: ICES SD 24-26; number of hauls: 12

In contrast to the expectations, based on the experiments conducted on a research vessel, the selectivity of the tested T90 s8-codend was not improved (in terms of reducing the discard rate). However, the catch of cod increased significantly within the length range of 34 to 44cm.

Comparison of total catches in numbers between Bacoma 120/105 (reference) and T90 s8 (test). Catches are divided by MLS (38cm)

	Numbers		Difference
	Bacoma 120/105 (reference)	T90 s8 (test)	
Cod			
< 38 cm	1644	1830	11.3%
≥ 38 cm	3722	4285	15.1%
Total	5366	6115	14.0%
undersized ratio	30.6%	29.9%	-2.3%



Proportion of the total catch caught in the test-codend (T90 s8). Dots indicate observed proportions for each length class, whereas lines indicate modelled values (solid line: mean value, stippled lines: 95 % bootstrap confidence intervals). Values below 0.5 indicate a reduced catch of these length classes in the test codend (T90 s8), compared to the standard codend (Bacoma 120/105)

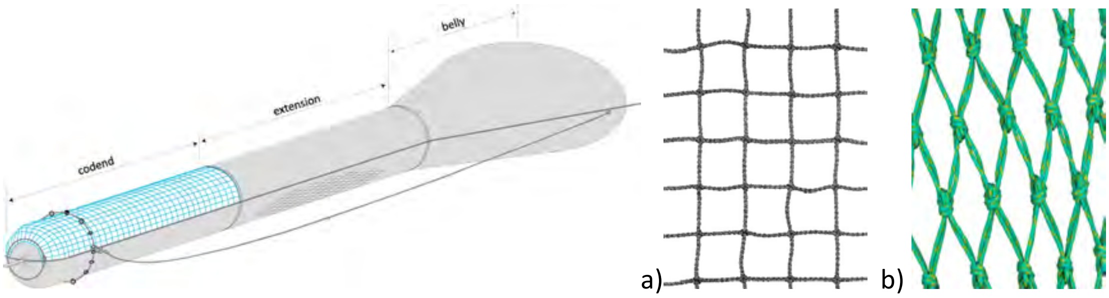
impact analysis

The short term economic performance of the tested codend is **106 %** of the reference codend (Bacoma 120/105 = 100%) at current legislation (no discard ban, MLS = 38 cm) and stock size distribution. Further information in the chapter "Impact study".

conclusion

In theory, an interesting option to improve the size selectivity of cod based on previous findings from scientific experiments. Nevertheless, during the test in commercial fisheries, the desired improvement in size selectivity of cod was not proven. The increase in catch efficiency resulted in improved economic performance.

Suggested gear 2: Bacoma 120/130



Left: Schematic drawing of tested Bacoma 120/130 - codend; Right: netting used in Bacoma-codend: a) 120 mm knotless square mesh; b) diamond netting in normal netting orientation

problem to solve/rationale

Indication of non optimal selectivity of the Bacoma 120/105 for cod, based on unbalanced selectivity properties (dual selection) between both nettings (120 mm square mesh netting and 105mm diamond mesh netting) used in the standard Bacoma-codend .This may result in simultaneous increase of the catch of undersized fish and commercial loss of cod. Additionally, both nettings are not optimal for flatfish selection.

science – fishery discussions

- problem: raised and discussed in the questionnaire survey, discussions with fishery and the workshop in 2012
- solution: one potential solution identified was the increase of lower panel mesh size
- rationale:
  - reduction of dual selection for cod
  - improvement of selectivity for flatfish species

gear developed and tested

The lower panel mesh size of the Bacoma-codend was increased from 105 mm to 130 mm diamond netting in normal orientation

Pros: cheap to build and easy to use Cons: -

tests and experiments

A) test of physical performance: Flume tank tests were conducted prior to the sea trials

Photographs of Bacoma 120/130 in flume tank, demonstrating the opening of the two mesh types during towing with 500 kg catch

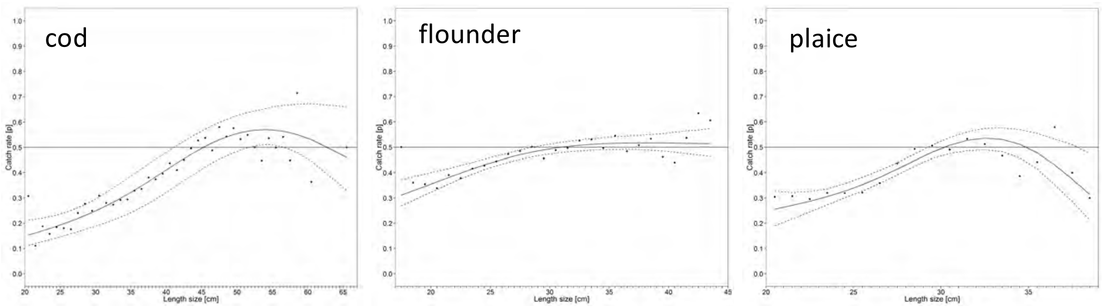
B) sea trial onboard FV “Lis-Hansa” R86 (DK)

when: April 2013; where: ICES SD 25; number of hauls: 21

The Bacoma 120/130 has shown a high reduction of cod below 45 cm, but also slightly higher catches above 45 cm. In numbers, there is a loss in catches above MLS, whereas in weight the loss is less. The increase in diamond mesh net size also gives a marked reduction in catches of flounder and plaice below 30 cm.

Comparison of total catches in numbers between Bacoma 120/105 (reference) and Bacoma 120/130. Catches are divided by MLS (for flounder, MLS for SD22-SD25 was used)

	Numbers		Difference
	Bacoma 120/105 (reference)	Bacoma 120/130 (test)	
Cod			
< 38 cm	6411	2864	-55.3%
≥ 38 cm	5713	4685	-18.0%
Total	12125	7549	-37.7%
undersized ratio	52.5%	33.4%	-36.4%
Flounder			
< 23 cm	1161	696	-40.1%
≥ 23 cm	8436	7501	-7.9%
Total	9597	8197	-11.1%
undersized ratio	12.1%	8.5%	-29.8%
Plaice			
< 25 cm	1538	712	-53.7%
≥ 25 cm	3215	2345	-27.1%
Total	4753	3057	-35.7%
undersized ratio	32.4%	23.3%	-28.0%



Proportion of the total catch caught in the test-codend (Bacoma 120/130). Dots indicate observed proportions for each length class, whereas lines indicate modeled values (solid line: mean value, stippled lines: 95 % bootstrap confidence intervals). Values of 0.5 indicate equal catches in specific length classes, values below 0.5 indicate a reduced catch of these length classes in the test codend (Bacoma 120/130), compared to the standard codend (Bacoma 120/105)

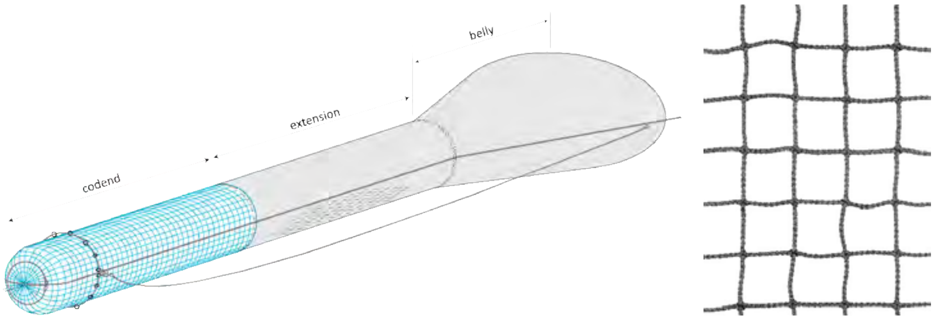
impact analysis

The short term economic performance of the tested codend is **89 %** of the reference codend (Bacoma 120/105 = 100%) at current legislation (no discard ban, MLS = 38 cm) and stock size distribution. Further information in the chapter impact study.

conclusion

The use of this codend, result in a reduction of the catch of undersized cod, flounder and plaice, calculated per fishing effort. Due to the loss of marketable cod, the economic performance was also reduced, compared to the reference gear.

Suggested gear 3: Square 120



Left: Schematic drawing of the Square mesh -codend; Right: netting used in Bacoma-codend (120 mm knotless square mesh)

problem to solve/rationale

Indication of non optimal selectivity of the Bacoma 120/105 for cod, based on unbalanced selectivity properties (dual selection) between both nettings (120 mm square mesh netting and 105 mm diamond mesh netting) used in the standard Bacoma-codend. This may result in simultaneous increase of the catch of undersized fish and commercial loss of cod.

science – fishery discussions

- problem: raised and discussed in the questionnaire survey, discussions with fishery at the workshop in 2012
- solution: one potential solution identified was the use of a full square mesh codend
- rationale:
    - eradication of dual selection for cod

gear developed and tested

The codend was made of knotless square mesh netting with a mesh size of 120mm, which is legally used for the construction of the escape-window in Bacoma-codends

Pros: well defined net opening during towing　　Cons: more expensive

tests and experiments

A) test of physical performance: Flume tank tests were conducted prior to the sea trials

Photographs of Square 120-codend in flume tank, demonstrating the shape of the codend and the opening of meshes during towing with 500kg catch

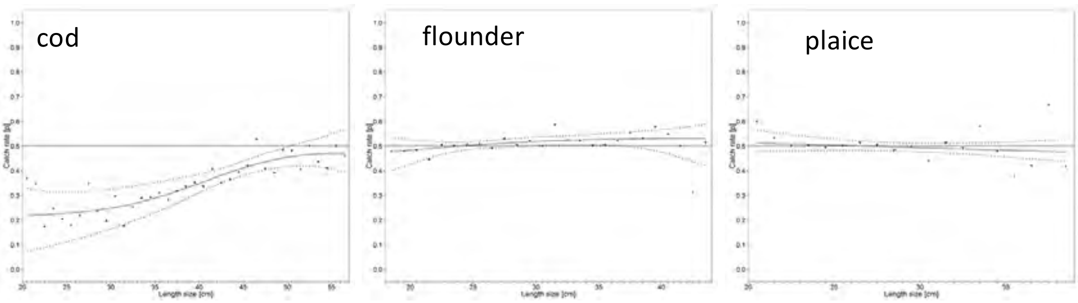
B) sea trial onboard FV “Lis-Hansa” R86 (DK)

when: April 2013; where: ICES SD 25; number of hauls: 21

The full square mesh codend Square 120 has shown reduced catchability for cod smaller than 50cm. This resulted in a high reduction of the catch of cod below MLS, but also a reduction of catch of marketable cod. Limited effects were found on the catch of flounder and plaice.

Comparison of total catches in numbers between Bacoma 120/105 (reference) and Square 120-codend. Catches are divided by MLS (for flounder, MLS for SD22-SD25 was used)

	Numbers		Difference
	Bacoma 120/105 (reference)	Bacoma 120/130 (test)	
Cod			
< 38 cm	2840	1095	-61.4%
≥ 38 cm	2911	1777	-39.0%
Total	5751	2872	-50.1%
undersized ratio	49.4%	38.1%	-22.79%
Flounder			
< 23 cm	1545	1452	-6.0%
≥ 23 cm	8332	8780	-5.4%
Total	9877	10232	3.6%
undersized ratio	15.6%	14.2%	-9.28%
Plaice			
< 25 cm	1641	1650	-0.5%
≥ 25 cm	3305	3304	-0.0%
Total	4946	4954	-0.2%
undersized ratio	33.2%	33.3%	0.4%



Proportion of the total catch caught in the test-codend (Square 120). Dots indicate observed proportions for each length class, whereas lines indicate modelled values (solid line: mean value, stippled lines: 95 % bootstrap confidence intervals). Values of 0.5 indicate equal catches in specific length classes, values below 0.5 indicate a reduced catch of these length classes in the test codend (Square 120), compared to the standard codend (Bacoma 120/105)

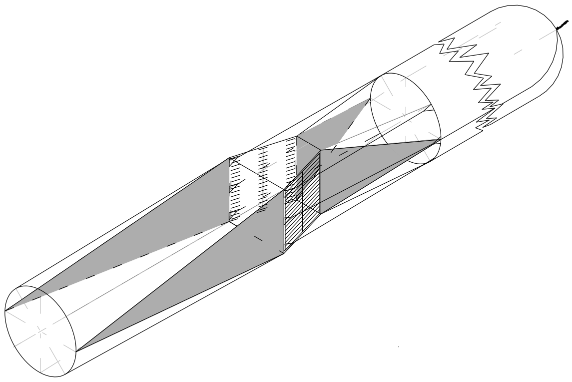
impact analysis

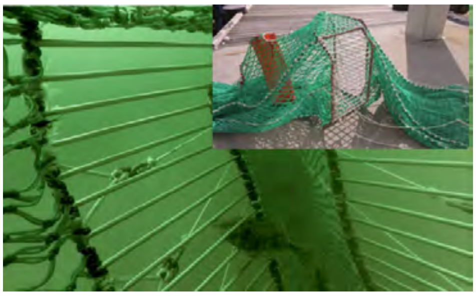
The short term economic performance of the tested codend is **77 %** of the reference codend (Bacoma 120/105 = 100%) at current legislation (no discard ban, MLS = 38 cm) and stock size distribution. Further information in the chapter "Impact study."

conclusion

The use of this codend, results in a reduction of the catch of undersized cod, calculated per fishing effort. Due to the high loss of marketable cod, the economic performance was also reduced, compared to the reference gear.

Suggested gear 4: Freswind Bacoma 120/105





Left: Schematic drawing of tested Freswind grid device; Right: underwater recording of netting used in Bacoma-codend and harbour picture of the Freswind, including the obstacle in front of the grid

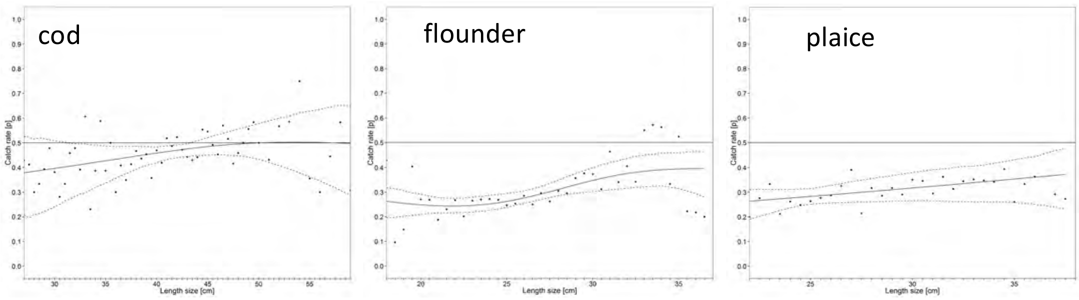
problem to solve/rationale
Flatfish species represent the largest proportion of bycatches in Baltic cod fisheries. Due to size and market reasons, a large fraction is discarded. These discards vary between areas and seasons. In addition to the problem of flatfish discards, the large amount of flatfish in the catches has a potentially negative influence on the size selectivity for cod, due to clogging.
science – fishery discussions

• problem: raised and discussed in the questionnaire survey, discussions with fishery and at the workshop in 2012
• solution: Swedish fishermen Vilnis Ulups (SIN77) proposed the usage of a lateral grid system, mounted in the last part of belly section (the conical part of the gear)
• rationale:
  ○ reduce the catch of flatfish species
  ○ adjust the size selectivity of flatfish species to future needs (future step)

gear developed and tested
Four evolutions of the original design were developed (from the original Vilnis-grid to the Freswind-device). These designs were tested and improved in four different cruises (the results of the final cruise on a commercial vessel are given below). The escapement windows in the present version are made of 2 steel grids (horizontal bars, bar spacing 38mm), which are fitted to each lateral side of the gear, at the end of the belly section. An inverted V-shaped canvas obstacle was attached in front of the grid area to alter the flatfish swimming direction sideways to the proximity of the grids Pros: clear defined escapement opportunity   Cons: more expensive, more difficult to handle
tests and experiments
A) sea trial onboard FV “Crampas” SAS107 (DE) when: March 2013; where: ICES SD 25; number of valid hauls: 12 The use of the Freswind reduced the flounder catches by 61 %, and plaice catches by 56 % in comparison to the reference codend (Bacoma 120/105). Additionally, total cod catches were also reduced by 12 %, whereas most reduction was observed for undersized cod.

Comparison of total catches in numbers between Bacoma 120/105 (reference) and Freswind Bacoma 120/105. Catches are divided by MLS (for flounder, MLS for SD22-SD25 was used)

	Numbers		Difference
	Bacoma 120/105 (reference)	Freswind Bacoma 120/105 (test)	
Cod			
< 38 cm	377	255	-32.4%
≥ 38 cm	1447	1347	-6.9%
Total	1824	1602	-12.2%
Discard ratio	20.7%	15.9%	-23.0%
Flounder			
< 23 cm	760	237	-68.8%
≥ 23 cm	2677	1096	-50.1%
Total	3437	1333	-61.2%
Discard ratio	22.1%	17.8%	-19.6%
Plaice			
< 25 cm	360	124	-65.6%
≥ 25 cm	1994	909	-54.4%
Total	2354	1033	-56.1%
Discard ratio	15.3%	12.0%	-21.5%



Proportion of the total catch caught in the test-codend (Freswind Bacoma 120/105). Dots indicate observed proportions for each length class, whereas lines indicate modelled values (solid line: mean value, stippled lines: 95 % bootstrap confidence intervals). Values of 0.5 indicate equal catches in specific length classes, values below 0.5 indicate a reduced catch of these length classes in the test codend (Freswind Bacoma 120/105), compared to the standard codend (Bacoma 120/105)

impact analysis

The short term economic performance of the tested gear modification is **96 %** of the reference codend (Bacoma 120/105 = 100%)) at current legislation (no discard ban, MLS = 38 cm) and stock size distribution. Further information in the chapter impact study.

conclusion

The results confirm that the Freswind-device can substantially reduce the unwanted catch of flounder and plaice in the Baltic cod fishery, while almost catching similar amounts of cod above MLS.

This could also be a promising species selection device to reduce flatfish catches in other mixed fisheries targeting round fish species.

Impact study

Short-term economic impact of suggested technical measures on different stock size class distributions

The aim of the economic impact study was, through theoretical scenarios; to evaluate the short-term effects of different technical measures and how these measures may interact with different size class structures of the Baltic cod stocks. The economic performance of a fishery is directly dependent on quota, stock size and size distribution of target species, as well as technical measures. We have analysed the economic impact of 60 different scenarios built around four main factors. The factors defining the scenarios are gear selectivity (Technical study - Suggested gear 1 to 4 compared to the Bacoma 120/105 reference codend), MLS (35 and 38 cm), discard ban (no and yes), and the three size distributions of cod in the stock (1990s, 2000s and 2010).

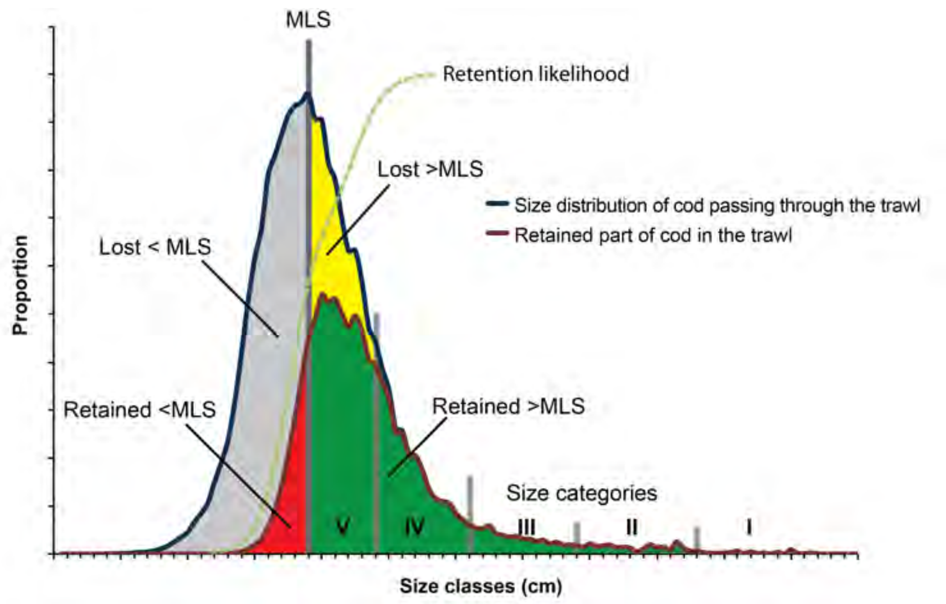


Figure IV. Theoretical example of retained and lost parts of the total size distribution of cod depending on gear retention likelihood. The grey area represents the amount of fish passing through the trawl that is not retained and that is below MLS. The red area represents the amount of fish that will be caught and discarded. The yellow area represents the amount of fish above MLS, which is not retained. The green area is the catch above MLS, which is divided in the 5 EU commercial size categories (I to V, where V is the smallest size category). The amount of fish in the red area will be landed in a scenario with a discard ban and discounted the quota but not giving any revenue.

Catch compositions for the different scenarios were calculated by multiplying the theoretical relative number of individuals in each size class in the respective stock with the retention likelihood for each size class and gear (Figure IV). This procedure generated the number of individuals retained in the trawl and lost in each size class in each combination of size distribution and stock. The economic analysis was based on a model calculating the revenues and costs for a vessel fishing its yearly quota in each of the different scenarios. Revenues were calculated as the landings times the price for each of the size categories. Total cost was the days at sea necessary to catch the quota (*DAS*) times the cost of operating a vessel one day.

On average, the single largest factor affecting the economic outcome was the stock size class distribution (on average 71 % greater outcome for 1990s distribution compared to 2010s distribution), followed by gear selectivity (on average 11 % greater outcome with the T90 120 s8 codend compared to Square 120 codend), followed then by changed MLS (on average 11 % greater outcome with MLS 35 cm compared to 38 cm) and finally the discard ban (on average 8 % higher outcome with no discard ban).

We conclude that if a discard ban would be introduced today, with current size distribution (period 2010) and with the current legislation (MLS 38 cm, Bacoma 120/105 or T90 120), it would result in decreased economic performance. A reduced minimum landing size (MLS: from 38 to 35 cm) is a possible way to minimize the negative economic effect of a discard ban (Table I). The most important single factor affecting the industry's economic performance was the size distribution of the cod stock, but management only indirectly influences this factor. The short term economic performance is in most cases lower when using more selective gear compared to the Bacoma 120/105 reference trawl, but the differences in economic performance tends to be smaller when a discard ban is introduced.

Table I. Relative economic performance and catch of undersized cod compared to the present situation (Today) with no discard ban, MLS 38 cm and Bacoma 120/105 (Ref), in the Swedish Baltic cod trawl fishery.

Scenarios	Performance	Economic		Undersized catch	
	Gear/MLS	35 cm	38 cm	35 cm	38 cm
Today	Bacoma 120/105 (Ref)	-	1.00	-	1.00
Discard ban	Bacoma 120/105 (Ref)	1.09	0.77	0.23	0.76
	Bacoma 120/130	0.99	0.74	0.15	0.55
	Square 120	0.89	0.62	0.18	0.61
	Freswind Bacoma 120/105	1.05	0.75	0.21	0.70
	T90 120 s8	1.14	0.80	0.23	0.78

Medium-term forecast as a result of increased selectivity

The medium-term forecast focused on the biological consequences of gear selectivity taking the dynamic effects of selectivity on stock development into account. We run a forward stock projection with the *status quo* selection, i.e. Bacoma 120/105 (Ref), and then we compared it to a similar forward projection but assuming a retention likelihood based on the Bacoma 120/130 codend.

The shift from a Bacoma 120/105 (Ref) to a Bacoma 120/130 codend will in theory only affect catches of cod sizes between 30 and 42 cm. This shift in selection pattern was used to calculate the theoretical retained length classes of cod with the Bacoma 120/130 codend. Successively, we applied this selection on the length frequency distributions of cod caught by the Swedish cod trawl fisheries in 2013.

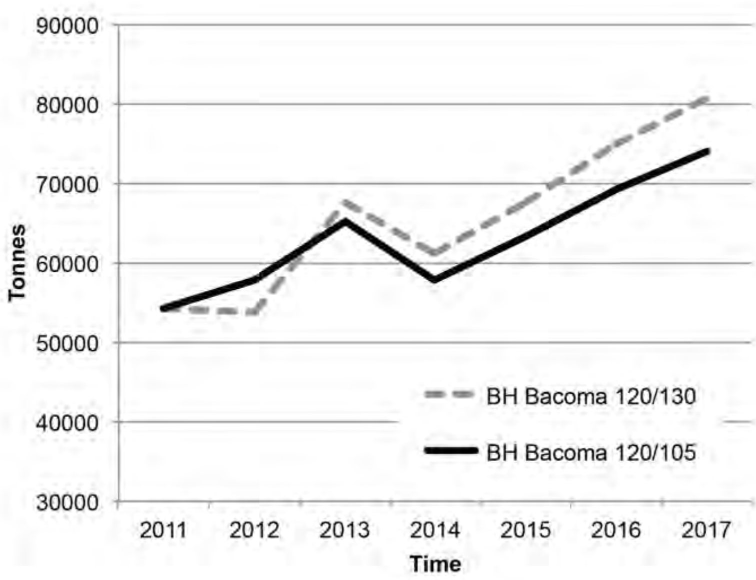


Figure V. Estimated catches for the Bacoma 120/130 and the Bacoma 120/105 (Ref) codend using recruitment as estimated with by a Beverton & Holt (BH) stock and recruitment curve based on the whole time series (1966-2012).

The medium-term forecast suggests that the Bacoma 120/130 codend would result in a slightly higher (approx. 1 % 2017) SSB irrespective of the recruitment type assumed. The use of a Bacoma 120/130 codend would also result in higher (8 %, 2017) catches compared to the Bacoma 120/105 (Ref) codend except for the initial year (Figure V). A shift from Bacoma 120/105 (Ref) to Bacoma 120/130 will introduce a decrease in catches the first year after the introduction. We conclude that the payback time in terms of catch of improved selectivity in the current state of the ecosystem is approximately a year given the current growth rate of the cod stock.

Recommendations

From these three studies (desktop, technical and impact) we recommend a combination of technical measures to further mitigate discards in the Baltic cod trawl fishery without jeopardizing the economy of the fisheries concerned.

- An increased selectivity (e.g. 130 mm diamond mesh instead of 105 mm codend with a Bacoma 120 mm window).
- A decreased minimum landing size/minimum conservation reference size (MLS/MCRS) to 35 cm.

By combining these two technical measures, a cost neutral solution (99 % of today's economic outcome with today's technical measures) for the industry can be obtained and at the same time the catch of undersized cod can be reduced to 15 % of the numbers discarded today (Table I).

With these changes, selectivity and the MLS/MCRS will be further separated compared to today, and would result in a significant reduction of catch of undersized cod in the trawl fishery of Baltic Sea. If the cod MLS/MCRS is kept at 38 cm, gear selectivity needs to be increased significantly in order to reduce catches of undersized cod to <5 % given the current stock structure. This would result in larger short term economic losses for the industry.

Table of content

Acronyms & definitions

ALK	Age Length Key
BACOMA	Codend type with a window with knotless square meshes (developed by the BAltic COd MAnagement project)
BITS	Baltic International Trawl Survey
BSRAC	Baltic Sea Regional Advisory Council
CFP	Common Fisheries Policy (of the European Union)
Codend	The narrow aft part of the trawl where fish are retained
CPUE	Catch Per Unit Effort
DATRAS	Database on Trawl Surveys
DCF	Data Collection Framework
DG Maritime Affairs and Fisheries	European Commission Directorate General responsible for Fisheries
Discards	Components of a fish stock thrown back after capture, e.g. because they are below the minimum landing size, or because quota have been exhausted for that species (most of the discarded fish will not survive)
GAM	Generalized Additive Model
GIS	Geographical Information System
High-grading	The discarding of a portion of a vessel's legal catch that could have been sold, in order to obtain a higher or larger grade of fish that will bring higher prices; may occur in quota and non-quota fisheries
IBSFC	International Baltic Sea Fishery Commission
ICES	International Council for the Exploration of the Sea
ITQ	Individual Transferable Quota
L50	50 % retention length
MCRS	Minimum Conservation Reference Size
Metier	Homogeneous sub-division of a fishery by fleet (e.g. the Dutch flatfish-directed beam trawl fishery by vessels < 300 hp in the North Sea)
MSFD	Marine Strategy Framework Directive
MLS	Minimum Landing Size
MMS	Minimum Mesh Size
MPA	Marine Protected Area
MSY	Maximum Sustainable Yield; the largest average catch or yield that can continuously be taken from a stock under existing environmental conditions
SD	Sub Division
SF	Selection Factor (L50/mesh size * 10)
SGTCOD	Study Group on Turned 90˚ Codend Selectivity, focusing on Baltic Cod Selectivity
SR	Selection Range (L75-L25)
SRA	Selection Ratio (SR/L50)
SSB	Spawning Stock Biomass; total weight of all sexually mature fish in the stock
STECF	Scientific, Technical and Economic Committee for Fisheries
Stock	A part of a fish population usually with a particular migration pattern, specific spawning grounds, and subject to a distinct fishery; in theory, a Unit Stock comprises all the individuals of fish in an area, which are part of the same reproductive process

T0	Standard netting in "normal" orientation
T90	Standard netting turned 90°, compared to T0
TAC	Total Allowable Catch
VMS	Vessel Monitoring System
WGBFAS	Baltic Fisheries Assessment Working Group
WGFTFB	ICES-FAO Working Group on Fishing Technology and Fish Behaviour
Window	A net-panel with meshes suitable to allow escapement of unwanted bycatch

1 Introduction

The Council of the European Union and the European Commission agreed at the 2009 October Fisheries Council to develop a roadmap to eradicate discards in the Baltic Sea. Political agreement on a new common fishery policy (CFP) was agreed on the 11th of June 2013, with an implementation of a discard ban as one of the major changes in the policy, which will be implemented into the Baltic cod fishery in 2015.

This report presents the findings of research carried out by Swedish University of Agricultural Sciences (SLU Aqua, SE), the Technical University of Denmark (DTU Aqua, DK), the Thünen-Institute of Baltic Sea Fisheries (TI, GER) and National Marine Fisheries Research Institute (MIR-PIB, POL) in collaboration with the fishing industry in these four countries to contribute to the eradication of discards in the Baltic Sea cod trawl fisheries.

Background to the study

Cod fisheries in the Baltic Sea date back a long way (MacKenzie et al. 2002), although more intensive exploitation only seems to occur since the 1950s (Bagge et al. 1994). The cod fishery further intensified in the early 1980s when the stock biomass substantially increased due to favourable reproductive conditions followed by a number of strong year classes (ICES 2013, Figure 1.1). Today, bottom trawling is the predominant fishing method in the fishery while hooks and gillnets dominated earlier.

In 2012 the Baltic Sea cod fleet include about 650 vessels. However, more than 80% of the total catches was harvest by the about 130 vessels larger than 12 m (STECF 2013 and WGBFAS 2013). In 2012, 75% of the total landings of cod were divided between the about 120 vessels in size classes between 12 and 40 m using active gears (trawls and purse seines, Table 1.1).

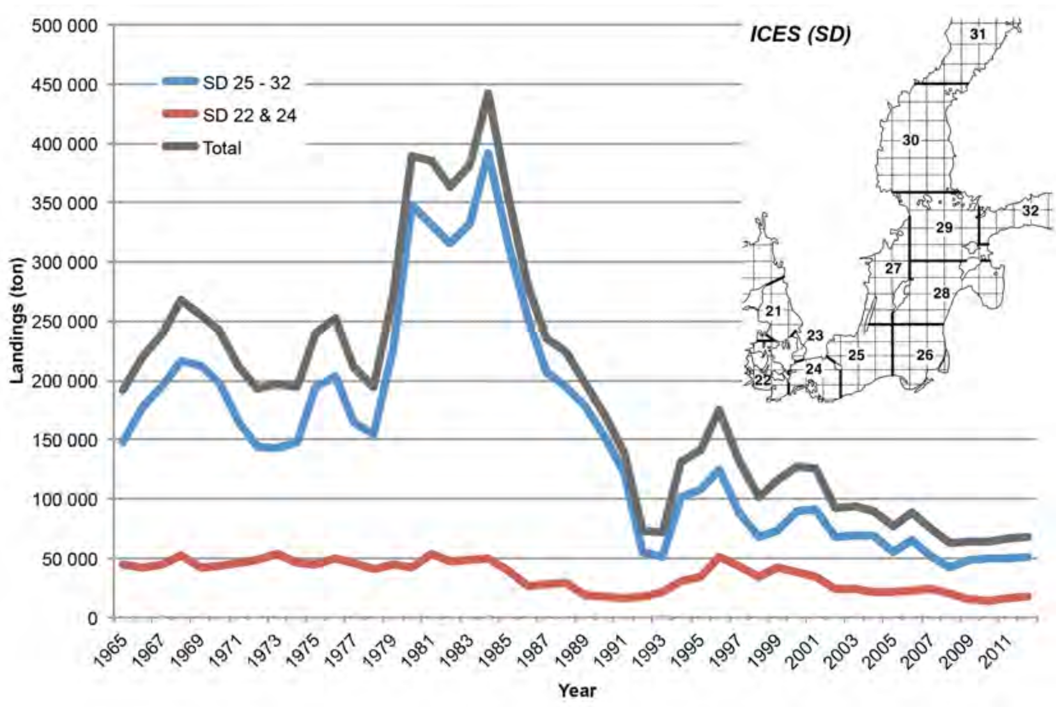


Figure 1.1. Total commercial landing of cod in the Eastern Baltic (SD 25-SD 32) and the Western Baltic (SD 22 & SD 24) between 1965 and 2012. The map is showing the ICES subdivisions (SDs). The main fishing ground today, for the Baltic cod trawl fishery is subdivision 24, 25 and 26. Subdivision 23 is closed for trawl fishery. In 2012 only 69 % of the total allowable catch (TAC) of cod was landed of the eastern Baltic cod stock and 80 % of the TAC of the western Baltic cod stock (ICES 2013).

Table 1.1. Relative landings of cod by the Baltic Sea cod fishery fleet in 2012 divided between active (trawls, purse seiners) and passive gears (nets, hooks, pot and traps), and vessel size classes.

Gear/Vessel size	<10 m	10-12 m	12-18 m	18-24m	24-40m	>40 m	Total
Active	<1%	2%	26%	25%	24%	<1%	78%
Passive	7%	8%	6%		2%		22%

Technical conservation measures also have a relatively long history in the Baltic Sea. Scientific studies of trawl modifications to reduce catches of young fish in trawls started in the early 1900s (Ridderstad 1915). Before most of the countries around the Baltic became EU members, the International Baltic Sea Fishery Commission (IBSFC) was responsible for fisheries management in the Baltic Sea. After its establishment in early 1970s, the IBSFC soon recognized that there was a need for investigating a mesh size increase, and many mesh size experiments were conducted. The work was further intensified in the mid-1990s but this time, the focus was changed from increasing mesh size to developing alternative devices to improve the size selectivity of the Baltic cod trawls (see Madsen 2007 for a review).

Gear regulations for cod trawls in the Baltic have changed many times during the last 20 years (Suuronen et al. 2007), and are now mainly gathered in EC Council regulation 2187/2005. Before 1994, the minimum mesh size (MMS) was 105 mm, when the IBSFC decided to increase MMS to 120 mm and minimum landing size (MLS) from 33 to 35 cm. At the same time, two other codend designs with selective escape windows in a 105 mm codend were introduced as legal alternatives to the conventional diamond mesh codend. This was one of the first European Communities regulated regions where selective sorting devices were adopted into legislation (Madsen 2007). In 2002 a new codend design with an escape window, the Bacoma codend, was introduced by the legislation, based on advice from the Bacoma project (Suuronen et al. 2000). In August 2003, the conventional diamond mesh codends were prohibited and Bacoma window mesh size was reduced from 120 mm to 110 mm (Valentinsson and Tschernij 2003).

For some years, the Bacoma codend was the only legal gear. In 2006, the T90 codend (netting tuned 90 degrees) was introduced as an alternative to the Bacoma codend. The next major change occurred in 2010 when the mesh size of the T90 codend and the Bacoma window was increased from 110 mm to 120 mm mesh size to further decrease discards. At the same time, a high grading ban for all quota species was introduced while the MLS was kept at 38 cm (EC Council reg. 1226/2009).

Despite all the changes, technical conservation measures related to gear are still much debated in regional forums and member states, especially in the light of the obligation to land all catches in a reformed CFP. ICES (2010) reported that cod discard rates in the demersal trawl fishery for cod in the Eastern Baltic varied with year, quarter, country and total catch weight. On a yearly scale, the average discard rate for all countries fluctuated without a clear trend around an average value of 10 % (Anon 2010). Annual variability in discard rates is to a large extent a result of variability in year class strength. Since 1996, approximately 77 % of the estimated discards of cod are from active gears (e.g. trawls and seine). However, in the estimates from 2012 this fraction for active gear was increased to almost 99 % of the total discards in number in the eastern Baltic (ICES/WGBFAS 2013).

Objectives and scope

The main aim of this study was to identify technical solutions, both economically and biologically sustainable, to mitigate the discards of cod in the Baltic Sea cod fishery.

The aim of the project was divided into three main tasks:

- Assessing the present knowledge on discard and causes of discard in the Baltic cod fishery, and to explore the temporal and spatial patterns of discard sensitive size classes of cod and of the fishery effort.
- Identifying technical solutions and suggesting final technical measures to further mitigate cod discard in the trawl fishery for Baltic Sea cod.
- Evaluating the possible impacts of the proposed technical solutions and technical measures on the stock assessment and the impact on the economy of the fisheries concerned.

These tasks were undertaken through a desktop study, a technical study and an impact study. In order to engage trawl fishermen in the project, a questionnaire was sent out in spring 2012. The aim was to establish a dialogue with the industry on selectivity, gear selection, discard patterns and management options, and to collect their views, problems and potential solutions to mitigate discards. A stakeholder workshop was held to synthesis the present knowledge; discuss the results from the questionnaire, and addressing a final technical solution. After the workshop engaged fisherman and netmakers enhanced the development of the suggested gear alternatives in collaboration with the project.

During consultations with the industry and stakeholders the project team was asked about the decisions taken to focus on trawl fisheries. On the one hand, the project focussed on the Baltic Sea cod trawl fishery since it is well documented that this fishery is the main source of cod discards in the Baltic Sea (ICES/WGBFAS 2013). On the other hand, the project has addressed these tasks from a strictly scientific perspective, and not considered political options such as quota transfers between fleet segments (e.g. moving quotas between active gears to passive gears) has not been part of the project. Further, the new CFP have been adopted after this project was initiated. We have included some of the major changes from the CFP in the impact analysis, as the landing obligation/discard ban, which we thought to be relevant for this study. However, either Marine strategy framework directive (MSFD) or the new CFP is fully operational in the Baltic Sea today.

The desktop study - Discard pattern and spatial and temporal distribution of discard sensitive size classes of cod

To assess the present discard problem in the Baltic cod fishery we have used data collected within the data collection framework (DCF), including survey data (Baltic International Trawl Survey, BITS), Vessel Monitoring System (VMS) data and catch data from the Sea sampling programme within the DCF. Further, the spatial and temporal distribution of discard sensitive size classes of cod has been modelled and the overlay of commercial size classes and fishery effort analysed.

The main objective of the desktop study was to provide an understanding of the discard problems to be solved in the technical study.

The technical study - Identification, design and testing of technical designs

After the technical review, several suggestions on technical designs were discussed directly with fishermen and netmakers, both during the preparation of the suggested designs and during the commercial vessel sea trials. Proposed technical solutions were tested in commercial vessel sea trials. The commercial vessel sea trials were conducted on board three commercial vessels, one from Denmark, Germany and Sweden, respectively.

The economic and biological impacts of the proposed technical solutions, tested in the commercial vessel sea trials in the technical study, were then analysed in the impact study.

The impact study - Impact evaluation of the proposed solutions

The impact study was divided into a short-term economic model exploring the economic performance under different management scenarios (different gear modification, different MLS and discard ban) for a standardized vessel, and a medium-term projection of a stock assessment affected by the selectivity of different trawl designs (e.g. codend).

Structure of the report

The structure of the report follows the three main tasks of the study. The results from the desktop study are presented in Section 2. Section 3 gives a technical review together with the results from the commercial vessel sea trials. In Section 4, we evaluate the impacts of the proposed solutions.

Conclusions from each section are discussed together with the outcome from the fishermen questionnaire, stakeholder meeting and direct interaction with the industry.

The report also contains a number of annexes, which provides further details on the data and methods used in the study. Annex 1 contains the outcome from the questionnaire and the workshop. Annex 2 provides details of the methodology on the model describing spatial and temporal distribution of discard sensitive cod and fishery effort. Annex 3 provides data and methods from the short and medium term impact studies. Annex 4 to 6 provide data and results from the selectivity experiments on board research vessels. Annex 7 provides the rational behind the size selectivity of the Freswind grid system. Finally, Annex 8 gives details on the statistical methods used for the catch comparison.

Interactions with the Baltic cod fishery

There was four major ways of interactions with the Baltic cod fishery within the project; 1) a questionnaire was sent out to active trawl fishermen fishing cod in the Baltic Sea at the time, 2) a workshop was held to discuss the outcome of the questionnaire, and suggest technical solutions, and 3) personal meetings with fishermen, netmakers and organizations, 4) The commercial vessel sea trial, where final suggested technical solutions was tested.

Questionnaire and workshop

The aim of the questionnaire and the following workshop was to engage trawl fishermen early in the project on the discussion on selectivity, discard patterns and management options giving us a picture of the occurring views, problems and potential solutions. The full report from the questionnaire and the workshop is presented in Annex 1. We received in total 64 answered questionnaires of totally 369 sent out. Above 70 % of the fishermen answered that they have been fishing cod in the Baltic Sea for more then 20 years and more then 80 % of the answering fishermen said that the Baltic Sea cod fishery was their main income from fishing today.

There was a common view by the fishermen that less than 10 % discards was an acceptable discard rate (Figure 1.2). However, about 25 % of the fishermen estimated the discard rate to be above 10 %, telling us that there is a common understanding by the industry to mitigate the discard rate of cod in the Baltic Sea cod fishery.

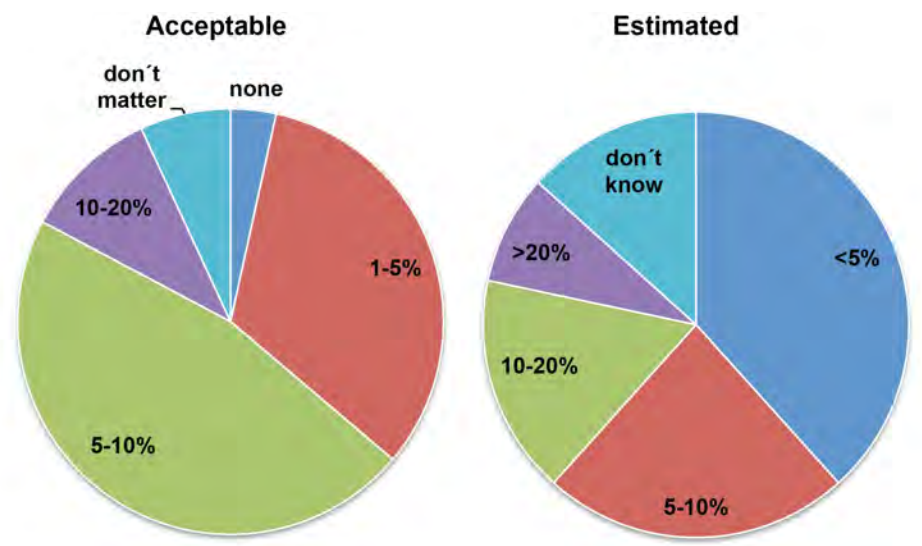


Figure 1.2 Acceptable and estimated discard rates (%) given by the 64 fishermen answering the questionnaire. The complete questionnaire is reported in Annex 1 together with the report from the workshop.

The risk of discards was considered by the responding fishermen to be a little higher in winter and spring, but all times of the year could have more than average discards, depending on the fishing area. There are good possibilities of communication between fishermen at sea and it is possible to receive information where the discard rich areas are. There was no general opinion from the industry if discard have increased or decreased over the last 5 years. Most fisherman (63 %) disagree that permanently closed areas are an effective measure to reduce discards, however almost half of the fishermen (45 %) agreed that temporally closed areas could be an effective way to reduce discards, especially if these areas are initiated by the industry themselves.

Almost 70 % of the fishermen answered that they preferred to use the Bacoma codend before the T90 codend. However, there were a lot of comments on failures in both codends, both concerning handling and selectivity. Increased selectivity compared to today's gears was thought by more than 50% of the answering fishermen as important or of some importance as a measure to reduce discards. This response differed significantly between fishermen from different countries.

This suggests that to spatially avoid aggregations of small cod and to improve selectivity could both be potential solutions to mitigate the discard of cod in the Baltic Sea.

The aim of the workshop held in Karlskrona, in May 2012, was to set up a platform for stakeholders to form an opinion on the feasibility of possible solutions identified by the research team and to discuss with the industry about their experiences and suggestions for further modifications as well as the challenges. The main outcome of the workshop was the identification of 8 potential designs to improve selectivity in the Baltic Sea cod fishery.

Personal meetings with fishermen, netmakers and organizations

The potential technical solutions was then further discussed with fishermen and netmakers before the number of designs was narrowed down to 4 designs, which all was included in the commercial vessel sea trial. This collaboration with fishermen and netmakers lead to the development of a grid system mounted in front of the codend to exclude flatfish before entering the codend. The design of the full square codend was develop together with netmakers at Nexø trawl. The final design of the full square mesh codend was refined together with the netmaker during the flume tank tests before the commercial vessel sea trial (see Technical study for further details). Further, the commercial vessel sea trial was a direct cooperation with the industry testing the final technical solutions aboard commercial vessels.

Technical workshop "Selectivity in Baltic Cod Fisheries Workshop" hosted by European Commission (EC), 4 September 2013

After the draft final report of the project was presented, a one-day technical workshop, hosted by the EC, was held in Brussels on the 4th of September 2013. The workshop was moderated by Mr Martin Pastoors and is reported by the EC. The project held 3 presentations at the workshop (Patterns and causes of discarding in the Baltic Sea and The selectivity options identified and tested in the Lot1 project). After this workshop participating stakeholders were invited to submit written comments on the project draft report. The project has received comments from two stakeholders (Krzysztof Stanuch, Baltic Net Ltd, and Niki Sporrong and Gustaf Almqvist The Fishers Secretariat (FISH) and Coalition Clean Baltic) and as far as possible incorporated a response to these comments into this final report.

2 Desktop study

2.1 Discard in the Baltic Sea trawl fisheries for cod

Introduction

The Baltic Sea trawl fisheries have been systematically sampled for discards since the mid-1990s. Since 2002, sampling is carried out according to EC data regulations (from 2009 onwards 199/2008, 665/2008 and 2010/93/EU). Data are collected by observers that join vessels during fishing trips. All unwanted catch of fish that is released back into the sea is defined as discards independent of the reason why it is released, even if the individual survive after being released back into the sea. Mortality induced by a fishing operation but not landed on deck is not accounted for in fishing mortality numbers in stock advice. This number of unallocated fishing mortality is most often unknown. The main end-users of the data on discards are the ICES assessment working group WGBFAS and in recent years STECF expert working groups that evaluate trends in fishing effort and exploitation patterns.

Observer data was made available to the project by Sweden (2002-2012), Denmark (2001-2010), Poland (2005-2010) and Germany (2002-2010).

The amount of discards recorded in this data varies substantially between trips and hauls. The total amount of discards in the 2730 examined hauls varied between 0 and 4.7 tonnes with a mean of 224 kg (standard deviation 422). The amount of cod discard varied between 0 and 3.3 tonnes with a mean of 127 kg (standard deviation 246). The discard fraction of the catch is dominated by a few species. In the eastern Baltic (subdivision 25-27), a total of 25 species were found in the discards but cod, flounder and plaice constituted 99.5% of the overall weight (Figure 2.1). In the western Baltic (subdivision 22-24), dab and whiting are common as well. In total, 52 were species found in discards.

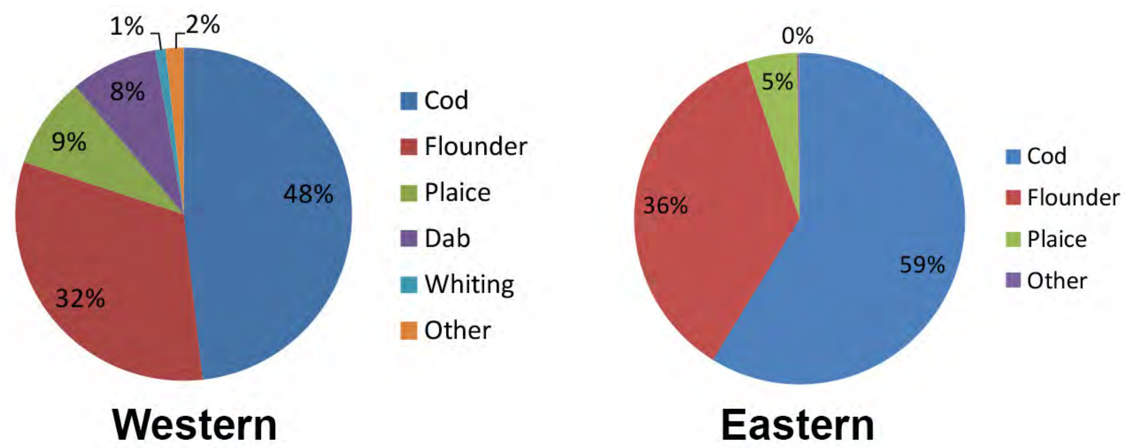


Figure 2.1. Species composition in discard in eastern and western Baltic trawl fisheries.

The vast majority (95 %) of the cod discarded during the observer trips are at or below minimum landing size (Figure 2.2). About 83 % of the discarded cod were between 30-37 cm in both number and weight. This is in line with what the fishermen reported when answering the project questionnaire (Annex 1: Interactions with the Baltic cod fishery), where the majority of fishermen consider a decrease of /to abandon MLS and/or improved selectivity as important management actions to reduce discards. Ninety percent of the discarded flounder (Figure 2.3) is above MLS, indicating that market considerations (low price) are a major reason for discarding. For plaice, approximately half of the discarded individuals are below MLS.

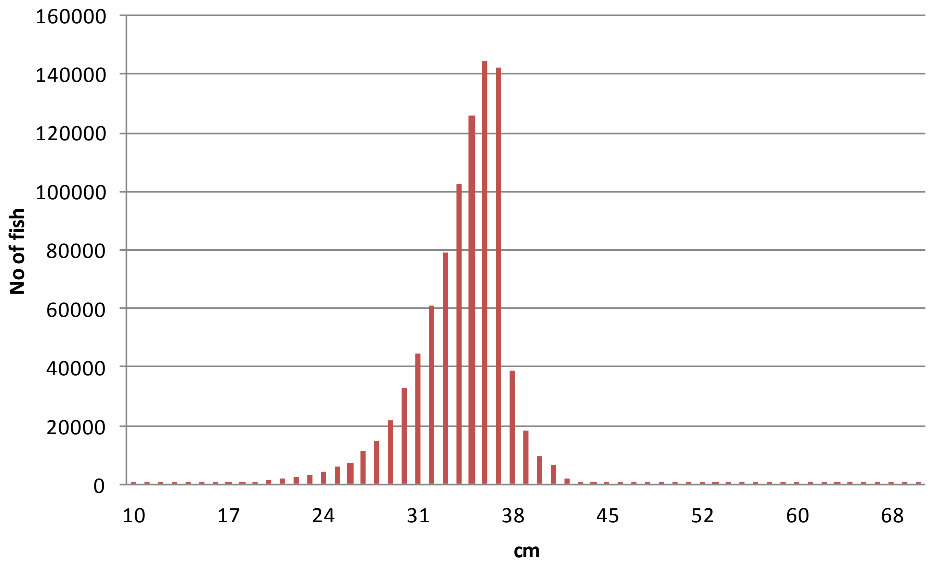


Figure 2.2. Length distribution of cod discarded during observer trips. MLS =38 cm.

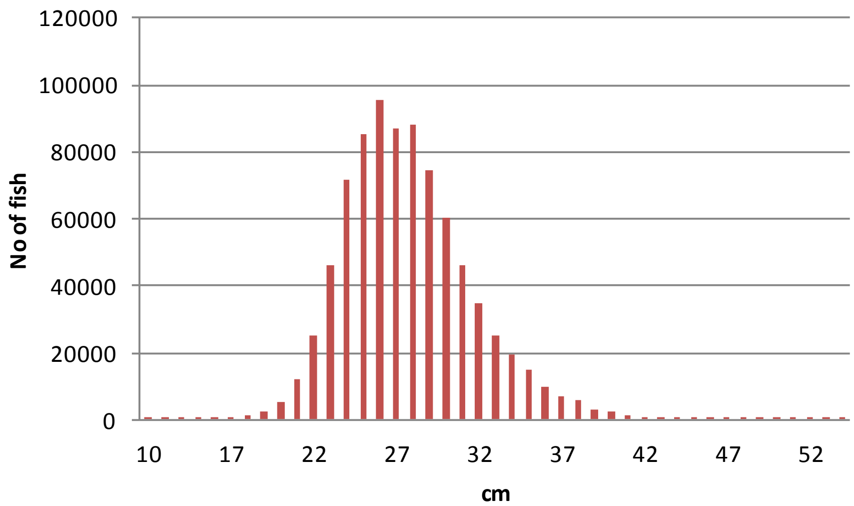


Figure 2.3. Length distribution of flounder discarded during observer trips. MLS =21-23 cm (depending on subdivision).

The discard rate of cod varies considerably between hauls. The overall mean is 10 %. The rate varies to some extent between years and countries (Figure 2.4 and 2.5).

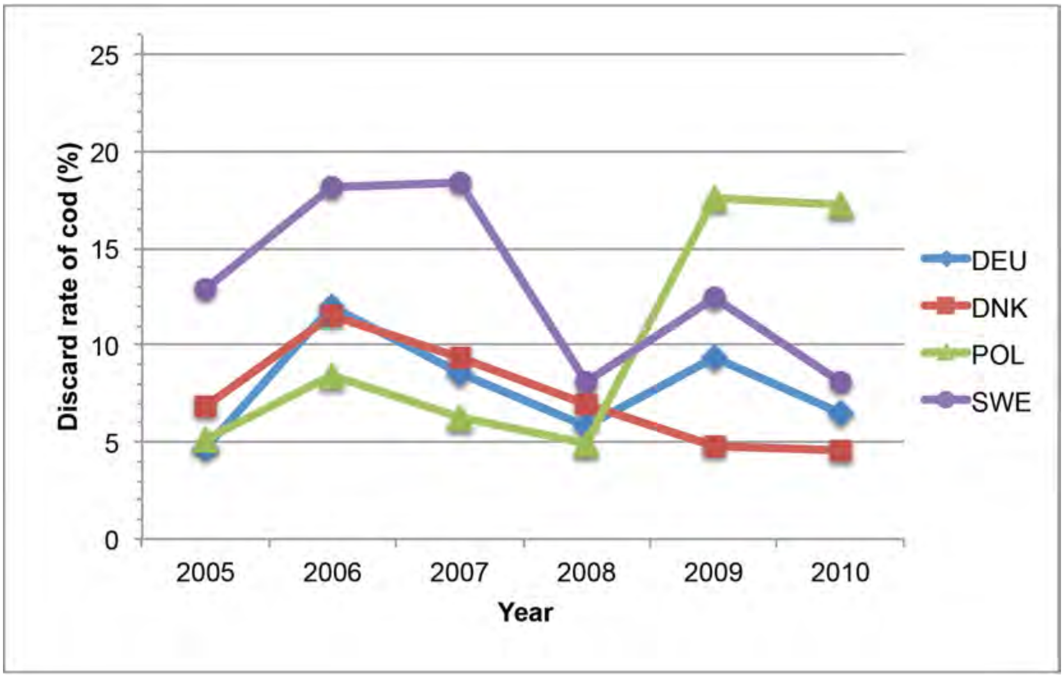


Figure 2.4 Discard rates from observer data by country, in the eastern Baltic trawl fisheries.

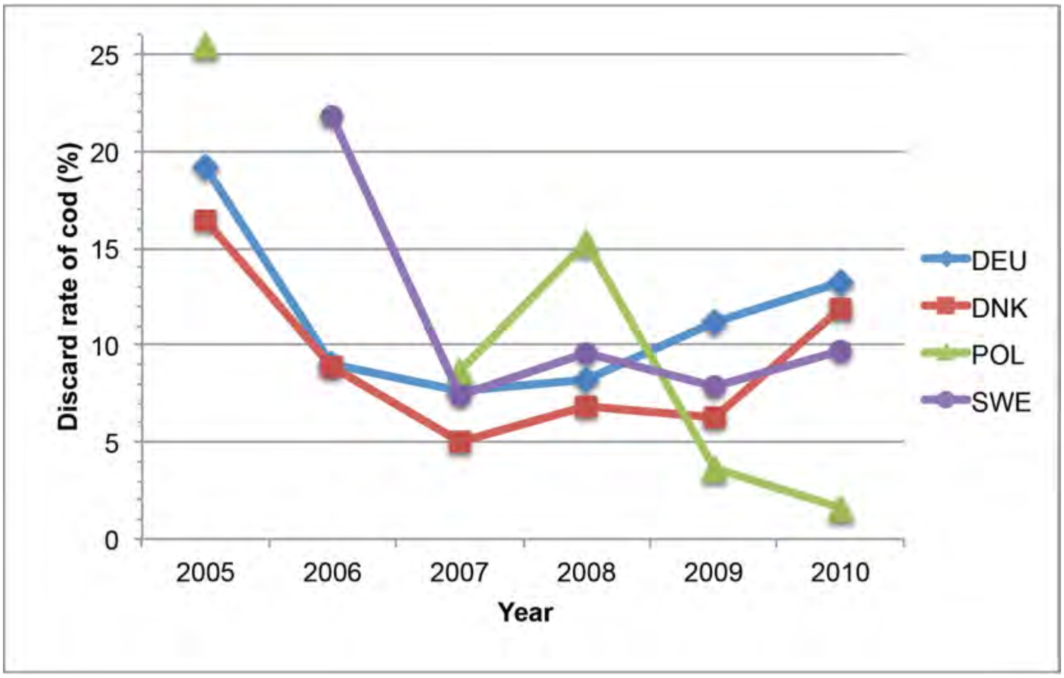


Figure 2.5. Discard rates from observer data by country, in the western Baltic trawl fisheries.

Note, that there is a large variance around the point estimates in Figure 2.4 and 2.5 as indicated in Figure 2.6. The indicated differences between countries are also reflected in the responses in the questionnaire (Annex 1: Interactions with the Baltic cod fishery). A larger proportion of the Swedish fishermen have answered that they have a discard rate of 10-20 % or >20 %, which is more, compared to the other countries. The overall mean, 10 %, is in the top end of what the majority of the fishermen answering the questionnaire found to be an acceptable level of discards.

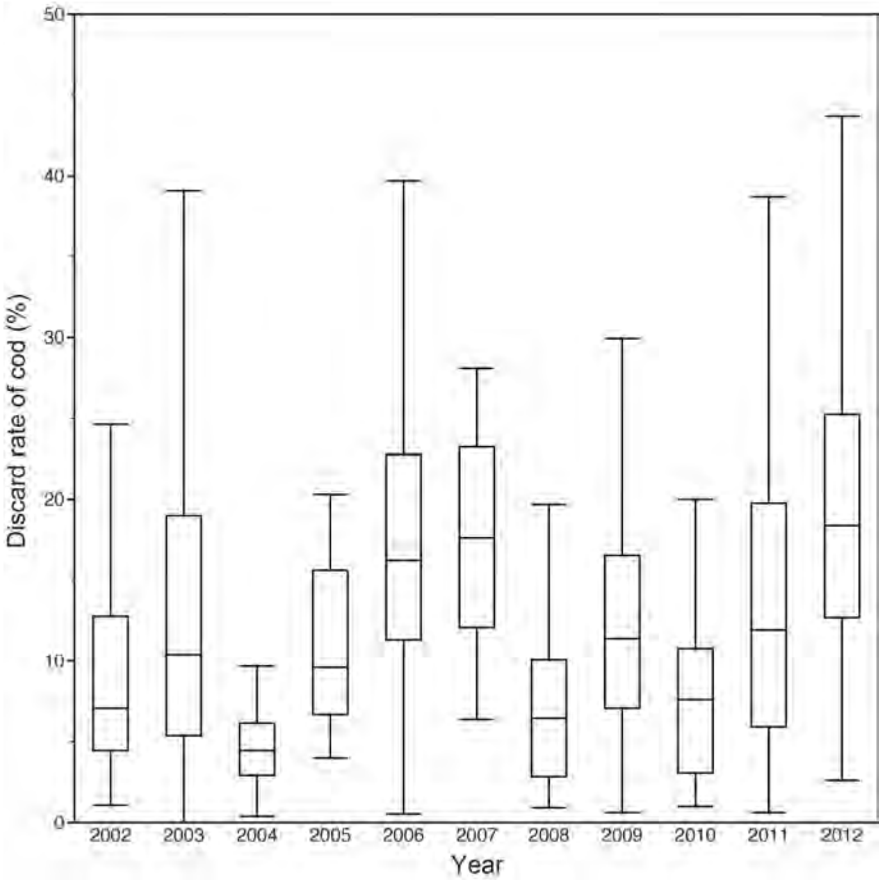


Figure 2.6. Boxplot showing discard rates of cod from observer data in the Swedish eastern Baltic trawl fisheries between 2002 and 2012. The plot shows 10, 25, 50 (median), 75 and 90% quartiles.

Factors affecting discard rates

Total catch size, the by-catch of flounder and vessel size have been suggested to have an impact on the discard rates of cod in the Baltic Sea cod fishery. From the observer data, this pattern was not clear, except for catches above 1500 kg of flounder, which increases the aggregated discard rate to about 17 % on average (Figure 2.7). The discard rate at very small catches of cod was also above the overall average (10±2 %), however most of these hauls were sampled in the western Baltic, targeting other species than cod. Therefore, further analyses were restricted to hauls with landings larger than 100 kg of cod, giving in total 1701 hauls for the whole data set.

Hauls were classified as low discard hauls, if the discard rate was less than 10 % of the total cod catch and high if the discard rate was between 30 and 50 %. In total, 1069 hauls were defined as low and 35 hauls were defined as high discard rate hauls. The mean value of the total catch in the low discard hauls was 1465 kg and in high discard hauls 1433 kg, suggesting no significant effects of total catch on discard rates (Fig.2.7). Similarly, the mean catch of flounder in low discard rate hauls were 79 kg and in high discard rate hauls 97 kg, indicating about 20 % more catch of flounder in high compared to low discard rates hauls.

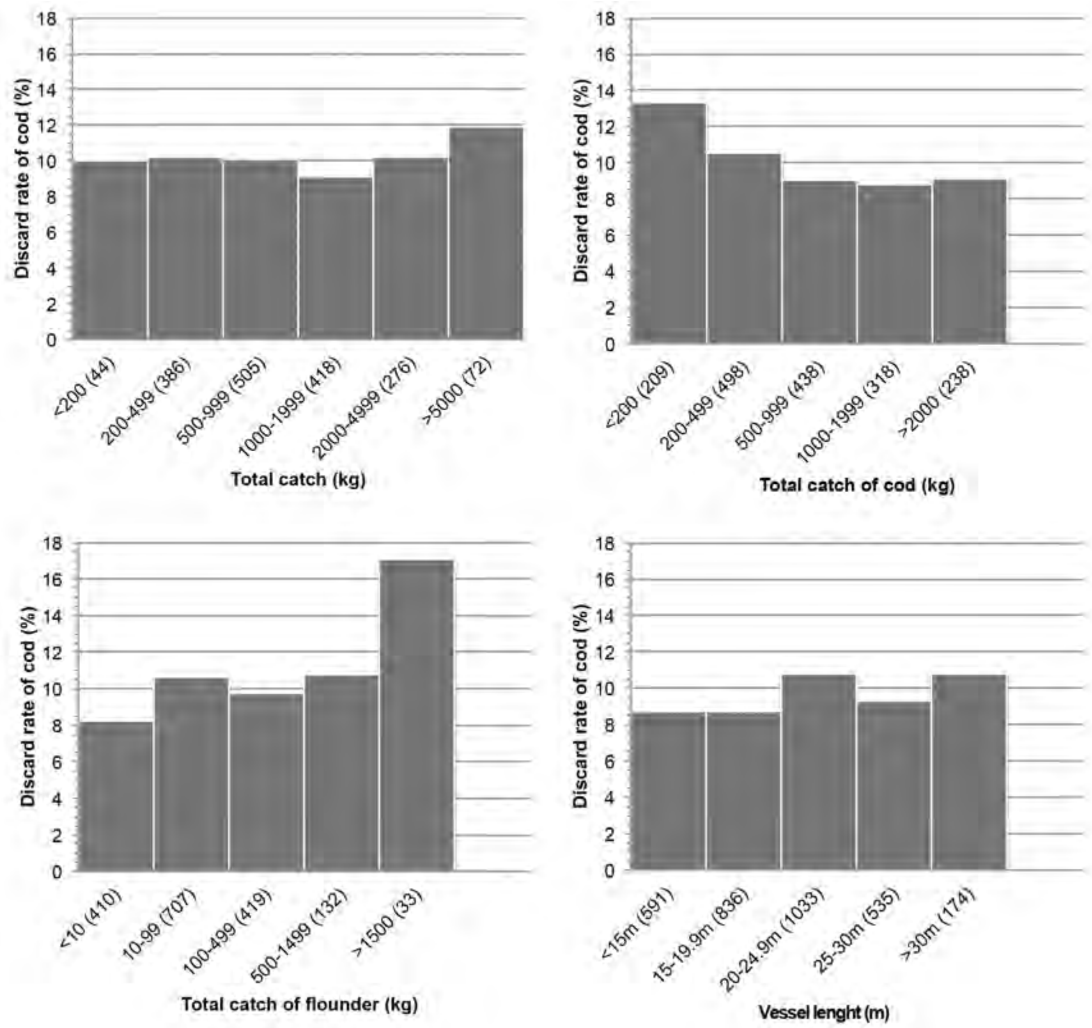


Figure 2.7. Accumulative discard of cod compared to total catch, cod catch, flounder catch and vessel size from hauls with more than 100 kg cod landed. Number in brackets is sample size.

Spatial patterns of discard

Space is also a factor that is considered to have an impact on discard rates. Within the project, we have identified areas where abundance of discard sensitive cod (30-37 cm) is persistently present (Annex 2: Modelling spatial and temporal distribution of discard sensitive cod and fishery effort). The position of high discard rate hauls (discard rate between 30 and 50 % of the total cod catch, n=35) is plotted against these persistency areas. Set positions of 18 out of 20 high discard hauls in the eastern Baltic were inside or nearby the outlined hot spot areas (Figure 2.8). The remaining 15 high discard hauls were observed in the western Baltic. In the persistence analysis of undersized cod, the western Baltic lacks hotspots. This is because, relative to the eastern Baltic, the density of undersized cod is significantly lower in the Western Baltic. The pattern coincides, at least to some degree, with the answers from the questionnaire, where cod discard seemed to be more in shelf areas.

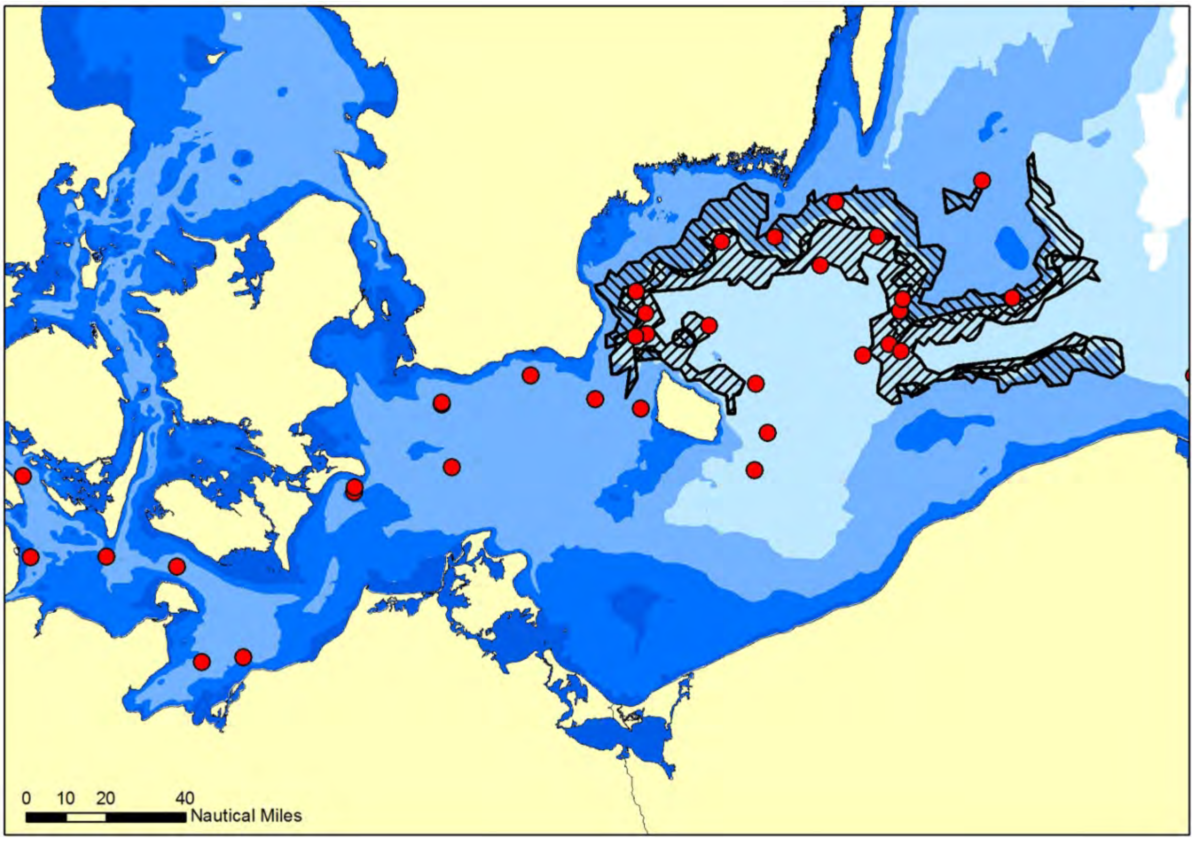


Figure 2.8. Map showing hatched areas with high density of undersized cod (30-37 cm) during both spring and autumn and red dots indicating set positions of high discard rates hauls (>30 % and <50 %,).

Conclusion

- The gross part of the discard in the Baltic cod trawl fishery during the investigated years (2002-2011) was undersized cod, 59 % in the Eastern and 48 % in the Western Baltic, of the total discard, followed by flounder and plaice.
- There is a large variation between years and countries in discard rates.
- Even though the discard rates of cod in the Baltic are considered relatively low (about 10 %) compared to other areas, the latest trend is that discard rates are increasing (ICES/WGBFAS 2013).
- Neither total catch, total cod catch or vessel size significantly affects the discard rates. However, huge bycatches of flounder (>1500 kg) may increase the discard rates of cod.
- There are an agreement between modelled areas of high density of discard sensitive size classes of cod (30-37 cm), the answers from the questionnaire and observed high discard hauls in the Eastern Baltic. However, this areas overlap with the major fishing grounds of the Eastern Baltic.

2.2 Modelling spatial and temporal distribution of Baltic cod and the effort of trawl fishery to evaluate area closures as potential measures to reduce discards

Introduction

The obvious method to reduce discards is to diminish the total fishing effort or introduce more selective gears. However, closed areas, both permanent and temporary, are potentially useful management measures if aggregations of discard sensitive species or discard size-sensitive groups of fish exist and can be identified.

In this context, knowledge of the spatial and temporal distribution of fish populations and the spatial and temporal use of the fishing grounds by the fishing fleet is crucial to enhance the understanding of why and where species are discarded. Taken together, this knowledge can be used to consider and predict the effects of closed areas on the status of targeted species as well as other components of the ecosystem i.e. sensitive habitats and non-commercial or protected species.

In the present study, we analysed the spatial distribution of cod and the cod trawl fishery in the Western and Eastern Baltic Sea (ICES subdivisions 22, 24 and 25-32) to predict the efficiency of area closures to protect juvenile cod and the impact of these closures on the activity of the trawl fishery. We used Baltic International Trawl Survey (BITS) data to model fish distribution and Vessel Monitoring System (VMS), combined with logbook information, to map fishing effort and landings. Identified persistent hot-spot areas of discard sensitive size classes of cod (30-37cm) under different management goal scenarios were then overlaid on the distributions of commercial size of cod (37+) and the trawl fishery effort to evaluate the performance of the closures and the potential cost to the fishery.

The analysis is composed of the following parts:

- Modelling the spatial distribution of three different size classes of cod (30-37, 38-48 and >48 cm)
- Estimating the hotspot areas of discard sensitive size classes of cod (30-37 cm)
- Estimate the most persistence hot-spot areas of discard sensitive size classes of cod (30-37 cm), suggesting the areas to be closed at different threshold values
- Overlaying the analysis of the hotspot areas of discard sensitive size class (30-37 cm) and the commercial size classes of cod (38-48 and >48 cm)
- Overlaying the analysis of the hot-spot areas of discard sensitive classes of cod (30-37 cm), the fishing effort and catch distributions of the commercial trawl fleet in the Baltic Sea
- From the overlay analyses, by year and quarter, quantifying the efficiency of the area closure in protecting discard sensitive size classes of cod and the cost to the fishery due to reduction in catch opportunities together with the potential reduction of the realised effort.

Material and Methods

Data collected

Data on the spatial and temporal distribution of cod are collected regularly during the Baltic International Trawl Surveys (BITS). We extracted the data from the ICES-DATRAS database for the period 2001 to 2011. Data on the abundance of cod by length classes were standardised by using conversion factors for respectively the combination of length class and gear used in the BITS survey during the time period, and area dependent length-weight relationships were used to convert cod abundance into biomass (WGBIFS, 2007). Length distributions of cod were then divided into one size class below the minimum landing size (Minimum landing size (MLS), 38 cm) and two size classes above it. The first size class corresponds to the most discard sensitive size classes (30-37 cm) of cod in the Baltic, the second (38-48 cm) corresponds to the EU commercial category 5 (which is the bulk of the catches in the Baltic trawl fishery) and the third size class (>48 cm) corresponds to EU commercial category 4 and above.

Modelling the spatial distribution of cod

The spatial distributions of three size classes of cod were reconstructed from bottom trawl survey data using regression kriging method, following the general structure:

$$Y(s_i) = \mu(s_i) + \varepsilon(s_i)$$

where $Y(s_i)$ is the observed value at location s_i, $\mu(s_i)$ is the mean effect or large-scale variation, and $\varepsilon(s_i)$ is the error part of the model or small-scale variation (Cressie 1993). A Box-Cox transformation was applied to achieve normality in the data.

A second order polynom on the depth was used for the deterministic part of the model, and an exponential variogram model was adopted to represent the spatial dependency of the data. Final kriging estimates were done on a 3 km x 3 km estimation grid over the whole study area (Figure 2.9; Step 1 [30-37 cm] and Figure 2.10; Step 1 [38-48 and >48 cm]).

Hotspot analysis

The recognition of the areas, that are potentially most sensitive to the practice of discarding, was based on the identification of areas with the highest concentration of discard sensitive size classes of cod (30-37cm). For this purpose, we used a hotspot analysis on the modelled distribution of cod to identify where discard sensitive size classes of cod aggregate during the investigated time period.

Hotspot areas were identified using three arbitrary thresholds of 25 %, 50 % and 75 %, which represent a wide range of conservation and management threshold levels (Bartolino et al. 2011; Figure 2.9; Step 2). In practice, these threshold levels are aiming to identify areas, which include 25 %, 50 % and 75 % of all the estimated number of discard sensitive size classes of cod (30-37 cm) in the distribution area of the stock.

Persistence analysis

Successively, the temporal stability of these hotspot areas was investigated by calculating the persistence index (Colloca et al. 2009). This index describes the relative persistence of a given cell as a hotspot, which indicates how often any given cell is selected for its high concentration of discard sensitive size classes of cod within the examined time series.

Finally, a polygon was calculated around those areas that obtained a score ≥ 0.50, which in practice corresponds to those cells selected as hotspot for at least 11 times over the 22 time steps (2 quarters x 11 years) used in the analysis (Figure 2.9: Step 3 and Figure 2.10; Step 2).

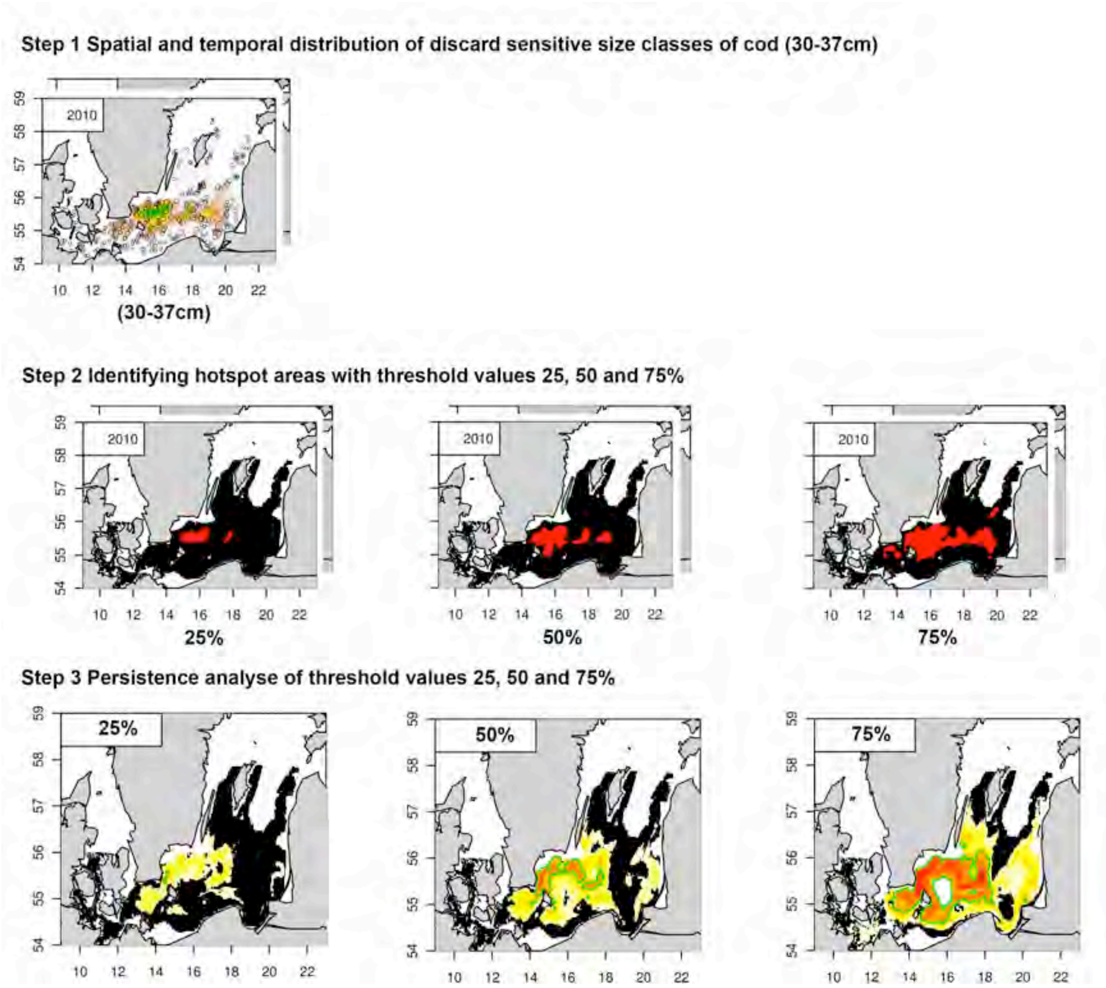


Figure 2.9. Schematic presentation of the analysis process. Step 1 and 2 include the analysis of the spatial distribution of each survey (year and quarter: shown here as stack of maps) **Step 1:** Modelling the spatial and temporal distribution of discard sensitive size classes of cod (30-37 cm). **Step 2:** Identifying hotspot areas of discard sensitive size classes (30-37 cm) with different threshold values (25, 50 and 75 %). **Step 3:** Persistence analysis of hotspot areas – with the suggested "closed areas".

Modelling of the spatial distribution of fishery landings and effort

Typical trawling speeds (1.5 to 3.5 knots) were selected from the VMS records. Logbook information on catch, species and vessel characteristics were associated to the VMS records using reported fishing time. This means that the total catch of a trip is allocated equally to each position within that trip. The fishing effort was calculated as the sum of pings times the vessel engine size (kW). Recently, an R-package*, vmstools,* has been developed (Hintzen et al. 2012) to facilitate the merging procedure between VMS records and logbook information. For the purpose of this study, the highly spatially refined landing and effort data were compiled at the national level and aggregated on a 3 x 3 nautical miles grid to monthly values between 2005 and 2010 of cod landings, total landings and effort (in kg and kW hours, Figure 2.10; Step 1).

Results

Overlay analysis

Following visual inspection of the persistence pattern, it was concluded that main hotspots overlapped for quarters 1 and 4. Accordingly, a scenario of area closures using the three conservation and management threshold levels of 25, 50 and 75 % was evaluated based on data from quarter 1 and 4 combined.

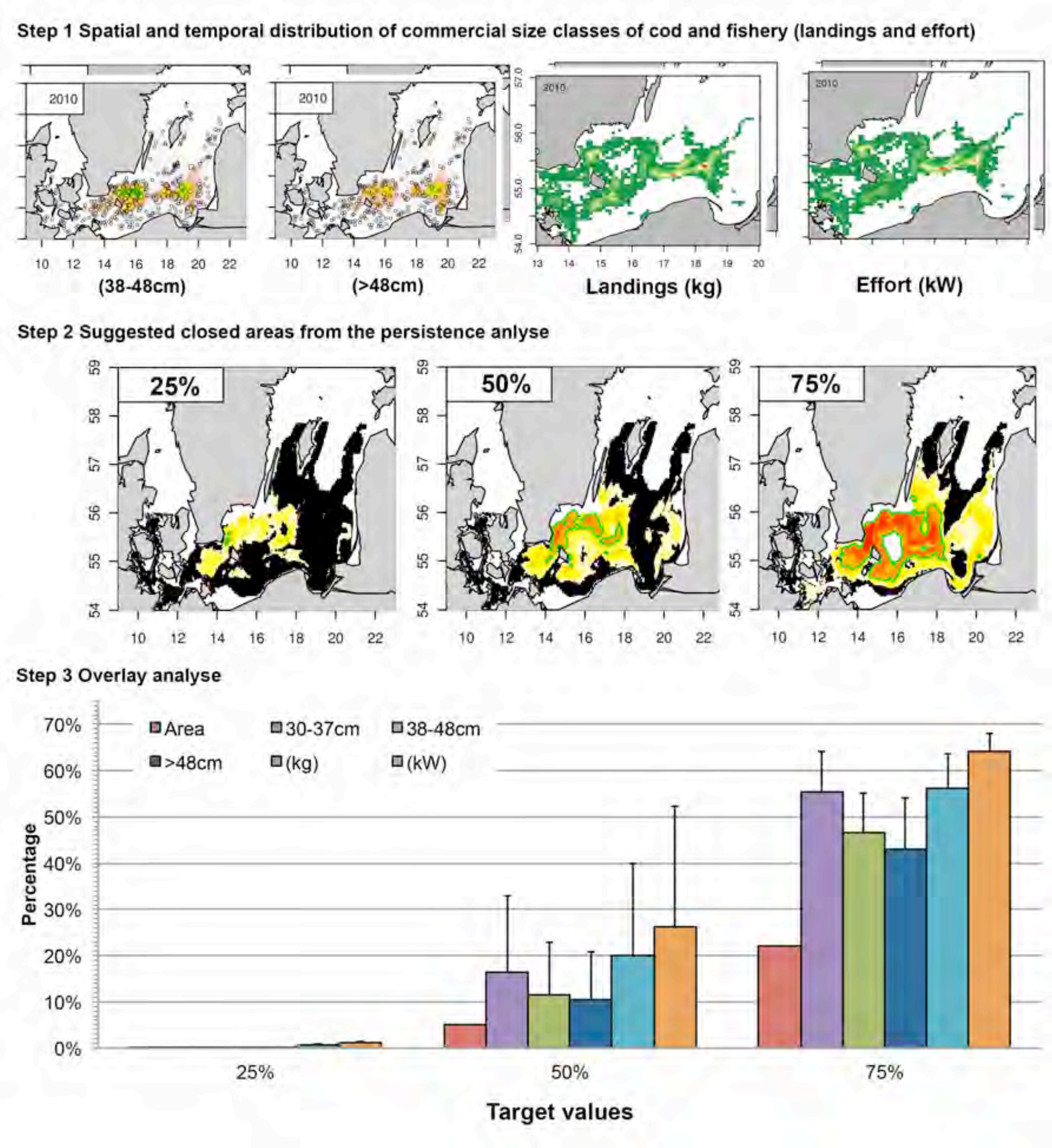


Figure 2.10. **Step 1:** Modelling the spatial and temporal distribution of the different commercial size classes of cod (38-47 and >48 cm) and the fishery (landings [kg] and effort [kW]) between 2005 and 2010. **Step 2:** Maps show the results of the combined persistence analysis for quarters 1 and 4 combined, with the green polygons outlining areas that are potential candidates for closure (Figure 2.9; Step 3). **Step 3:** Overlay analysis between the distribution of commercial size classes of cod and fishery and the candidate closed areas. The diagram shows the proportion of the candidate closed areas compared to the total area analysed, the average proportion of cod for each size class (30-37, 38-48 and >48 cm) and of the fishery (in mean landings [kg] and effort [kW]) in the closed areas.

The areas identified as hotspots more than 50 % of the time (green polygon area in Fig. 2.9; Step 3 and Fig. 2.10; Step 2) were used to evaluate the efficiency of area closure management measures in protecting discard sensitive cod as well as evaluating the conflict of an area closure with the fisheries as identified from the VMS and logbook information of the trawl fleet. The scenario was evaluated by estimating the proportion over time of the size class of fish located within the closure as estimated by the modelled distribution.

Overlay analyses of the different scenarios showed very low efficiency in protecting juvenile cod, (mean =0.18 % in numbers of discard sensitive cod potentially protected), using a management threshold of 25 %. Using management threshold of 50 and 75 % increases the efficiency significantly to 17 and 55 % in numbers of discard sensitive cod being potentially protected (Fig. 2.10; Step 3). There is large inter-annual variation of the location of the hotspots which could explain the low efficiency in protecting discard sensitive cod using the smallest threshold (25 %) i.e. protecting a small area will be inefficient due to high temporal variability in the cod spatial distribution.

Overlaying the management targets with the distribution of the commercial size classes of cod and the spatial distribution of the landings shows a considerable overlap. Closures corresponding to the management threshold of 50 and 75 % will imply a closure of 5 and 20 % of the cod distribution area, respectively and would conflict with the spatial distribution of effort by 27 and 63 %, and landings by 20 and 56 %, respectively (Fig. 2.10; Step 3).

Conclusions

The conclusions from the analysis of the distribution of discard sensitive cod, hotspot areas and the persistence analysis can be summarised as follows:

- The modelling approach allows us to identify hotspot areas with regular occurrences of different size classes of cod based on scientific survey data.
- Using hotspot identification and persistence analysis we are able to assess how large potential area closures need to be to reach different management thresholds in protecting discard sensitive size classes of cod.
- Discard sensitive size classes of cod in the Baltic are persistently concentrated in certain areas i.e. the Hanö bay and around the Bornholm basin.
- A large temporal variation in the overlap between discard sensitive size classes (30-37 cm) and commercial size classes of cod (38-47 and >48 cm), indicates that temporal closed areas could be more effective to protect discard sensitive size classes then permanent closed areas – real time closer system RTC.
- The overlay analysis of potential area closures with the distribution of commercial size classes of cod, fishing effort and landings conflict significantly with hotspot areas of discard sensitive size classes of cod indicating that an area closure will cause the effort to redistribute into adjacent fishing grounds and therefore increase the fishing effort in nearby areas if quotas (TACs) are the only measure to manage the fisheries.

3 Technical study - Identification, design and testing of technical designs

3.1 Introduction

The Baltic Sea is one of the areas where most selectivity experiments over time have been conducted (Madsen, 2007). In 1995, the Baltic Sea was one of the first EC-regulated regions where selective sorting devices were adopted into legislation in the trawl fishery (Madsen, 2007). Technical regulations aimed at improving selectivity have been a major management strategy since and regulations have been changed on several occasions in later years to improve selectivity. It has recently been demonstrated that the implementation of selective fishing gears has a significant effect on reducing cod discards in the Baltic Sea (Feekings et al., 2013).

As part of the technical study we reviewed the most important literature in relation to improving the selectivity of the fishing gears used in the Baltic Sea. The main focus is on cod catches in trawl fisheries that contribute to the major part of the discard and where most of the literature focusses. Flatfish studies are scarce and less documented in the available literature for the Baltic Sea.

Legislation concerning selectivity

Several changes in the technical measures aimed at improving size selectivity in the Baltic cod trawl fishery were applied in recent years. Two council regulations (88/1998 and 2187/2005, and their amendments) define the technical measures framework for the fishery (). Additional technical measures were introduced in the annual council regulations fixing fishing opportunities. The resulting changes in the size selectivity of cod are illustrated in Figure 3.1. The estimated L50 values (50% retention length) are indicated. The estimated effect of the changes in selectivity is stepwise increase in L50, giving a total increase of about 15 cm for the period investigated. Until 1995, selectivity was regulated solely by increasing the mesh size (Madsen 2007). In 1995, the first selective devices were introduced into the fishery (Madsen 2007). Known as the Danish window and Swedish window (Figure 3.2), the codend consisted of a 105 mm square-mesh window and was an alternative to a standard 120 mm diamond-mesh codend. An improved version of the Danish window, referred to as the New Danish window, was introduced in 1999 (Figure 3.1). In January 2002, the Bacoma codend with a 120 mm square-mesh window (Figure 3.1) in the top panel was implemented in the demersal trawl fishery as an alternative to a standard 130 mm diamond-mesh codend (Madsen 2007; Suuronen et al. 2007). The increase in L50 (~10 cm) (Figure 3.1) was too high and caused significant short-term economic losses for the fishery (Tschernij et al. 2004). Subsequently, the Bacoma 120 mm codend was either replaced with the less selective alternative (standard 130 mm codend) or manipulated to decrease its selectivity (Suuronen et al. 2007). To encourage fishermen to use selective codends, the MLS of cod was increased from 35 to 38 cm (Figure 3.1) (Suuronen et al. 2007). Following the MLS increase, the standard 130 mm codend was prohibited and the mesh size of the Bacoma window was decreased to 110 mm. This mesh size better matched the new 38 cm MLS (Valentinsson and Tschernij 2003). A new codend type, the T90 110 mm codend (meshes turned 90 degrees, Figure 3.1), was introduced in 2006 (Suuronen et al. 2007) as an alternative to the Bacoma 110 mm codend. This codend is made of standard diamond mesh netting, which is turned 90°. In 2010, the minimum mesh size of the Bacoma window and the T90 codend was increased to 120 mm (referred to herein as New Bacoma 120 mm and T90 120 mm codends). The length of the Bacoma window was also extended. The latter measure was to prevent selectivity from decreasing at high catch rates when the catch accumulation extent the Bacoma-window (ICES 2009; Madsen et al. 2010).

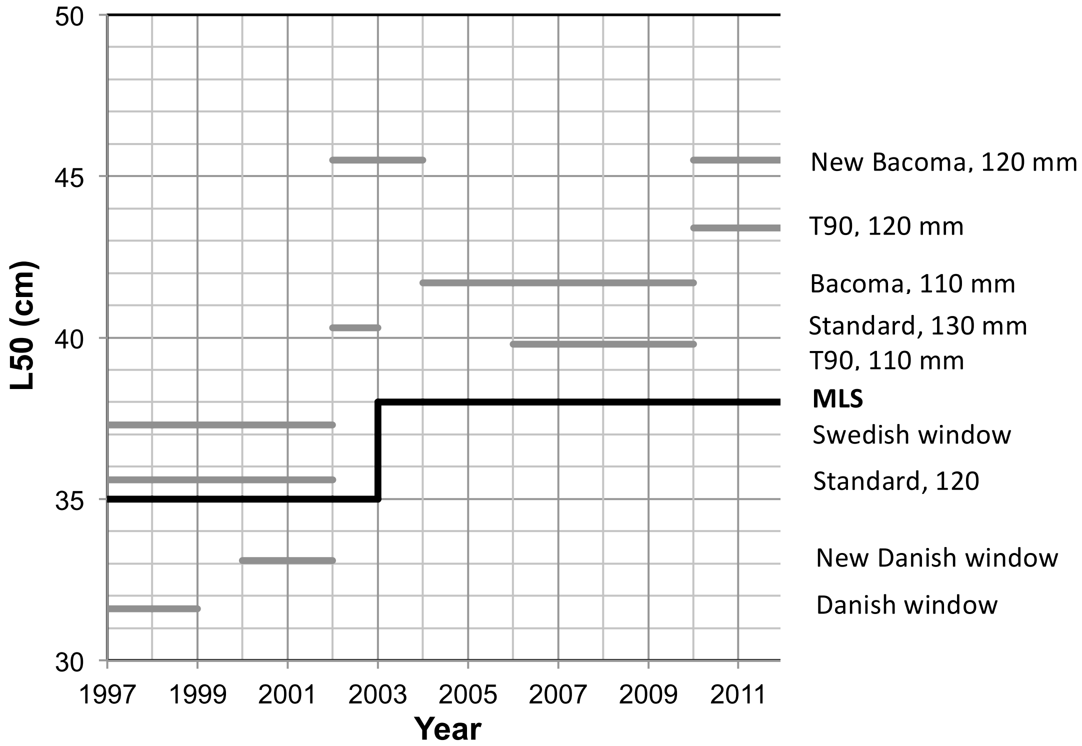


Figure 3.1. Schematic presentation of changes in codend selectivity (L50) and in Minimum Landing Size (MLS) relevant for trawl fishery targeting Baltic cod throughout the study period 1997-2010. L50 indicates the length of an individual that has a 50% probability of being retained after entering the codend. The minimum mesh opening was set to 120 mm (Bacoma) from 1st January in subdivisions 22-24 and from 1st March in subdivisions 25-32, in 2010. The L50 for the T90 120 mm codend is taken from Wienbeck et al. (2011). All other L50 values are taken from Madsen (2007). The same selectivity estimates are used for the Bacoma 120 mm and the New Bacoma 120 mm since the difference in the window length is not expected to make any difference in relation to the used selectivity estimates obtained with relatively low catch rates. The figure is modified from Feekings et al. (2013).

Behaviour of cod in relation to the capture process

The selection of fish by a fishing gear is defined to be the process which causes the catch of the gear to have a different composition to that of the fish population in the geographical area in which the gear is being used (Wileman et al., 1996). In this context, the selectivity of fishing gears is the central theme. The selection process can be described by the contact-selection curve, which is the probability that a fish of a given length is captured given that it contacted the gear (Millar and Fryer, 1999).

In general, roundfish respond to an approaching trawl at a greater distance and have faster bursts and swimming capabilities compared to flatfish (Ryer, 2004). The response of roundfish however differs from species to species. For example, cod react differently compared to other gadoids like haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), saithe (*Pollachius virens*) both in the mouth of the trawl and inside the trawl where they generally stay in the lower part of the trawl (Main and Sangster, 1985; Thomsen, 1993; Engås et al., 1998; Ingolfsson and Jørgensen, 2006; Krag et al., 2009a, 2009b; Holst et al., 2010; Krag et al., 2010;). It has been known for a long time that the main escapement of fish in the trawl occurs through the codend meshes (Beverton, 1963), and more specifically directly in front of the catch. In this region, conventional diamond meshes will have a high degree of mesh opening once the catch has started to accumulate (Pope et al., 1975; Engås et al., 1988; Robertson and Stewart, 1988). In front of this region the mesh opening of conventional diamond meshes will be smaller which will reduce the selectivity. Swimming performance will depend on cod size and water temperature (He, 1991, 1993) and will likely influence their ability to escape.

Little is known about cod behaviour in relation to the capture process of set nets. Capture rates of cod, caught by gill nets, are generally low (Holst et al., 2002; Hovgård et al., 1999), making it difficult to obtain comprehensive underwater observations. Generally, gill nets are anchored on the seabed and the capture process will depend on the cod swimming into the netting. The approach behaviour of cod in relation to a set net might influence how it gets entangled in the net and thus the selectivity of the net. If the cod is unaware of the gill net, it might hit the net harder influencing the probability of being retained by the net. Dickson (1989) suggested that selectivity could be affected by the presence of net floatation as well as fish caught in the net, since it could cause awareness of the net. The dominant method of capture for cod is gilling (Hovgård, 1996; Hovgård et al., 1999; Holst et al., 2000; Wileman et al., 2000), where the cod is enmeshed by having a mesh tight round the body, in most cases just behind its gill covers. Cod larger than the gilled individuals can be caught by having their maxillaries enmeshed (Hovgård, 1996; Hovgård et al., 1999; Wileman et al., 2000). Cod smaller than gilled individuals can be retained if they are entangled by their teeth (Hovgård et al., 1999; Holst et al., 2002; Wileman et al., 2000). Kallayil et al. (2003) found that use of baited gill nets increased the encounter rate but not catch rates. Cod swam slower in the vicinity of bait but did not stay for a longer time.

Escape windows

The escape window (henceforth window) is a panel with meshes (type and size) suitable to allow the escapement of unwanted bycatch. Typically, square mesh panels are inserted in the trawl (mainly in the codend region), which ensures that meshes stay open in this region. The remaining part of the trawl is most often made of traditional diamond mesh netting.

Several different types of windows have been tested in the Baltic Sea cod fishery. The first experiments were conducted in Sweden (Tschernij et al., 1996) testing codends with two side windows, which terminated close to the end of the codend. This codend is known as the "Swedish" or "Exit Window" (trademark). This codend is illustrated in Figure 3.2B. The "Swedish" codend had a relatively high SF (selection factor: L50/SR; L50: 50% retention length; SR: selection range) and relatively low SR compared to the conventional diamond mesh codend (Tschernij et al., 1996).

Danish experiments were conducted with codends where the two windows were placed in the sides of the lower panel below the selvedges ending in front of the lifting strop (Lowry et al., 1995; Madsen et al., 1998). This codend is known as the "Danish window" codend and is shown in Figure 3.2C. The first Danish experiments (Lowry et al., 1995) with the "Danish window" indicated that the SF was higher compared to the conventional codend but lower compared to the Swedish experiments with the "Swedish window" codend. Later experiments gave a relatively low estimated SF for a "Danish window" codend (Madsen, 1998) compared to the first experiment (Lowry et al., 1995). The different results for the two experiments with the "Danish window" codend could be explained by very different catch rates. Unsuccessful attempts were made to improve the selectivity properties of the "Danish window" codend by using contrasting colours (Madsen, 1998).

Later experiments (Madsen, 2000) indicated that the selectivity was improved when the window was moved aftwards (Figure 3.2D), ending at the same position as the Swedish window, close to the end of the codend. This might explain some of the observed differences between the “Danish window” and “Swedish window” codend types, obtained in earlier experiments. This codend (Figure 3.2D) is known as the “New Danish window”.

Further comparisons (Madsen, 2000) indicated that the selectivity could be further improved using a codend with a single top window (Figure 3.2E) but the catches were low when this experiment was conducted. The top panel window codend was then compared with a conventional diamond mesh codend in a mesh size experiment using a twin trawl rig (Madsen et al., 2002). The top panel window codend had a substantially higher SF (about 30 %) and a lower SR (about 20 % at the same L50) than the conventional codend. The top panel codend was named the “Bacoma window”. There was a negative effect of catch size on L50 of the standard codend but not on the Bacoma codend.

The original Bacoma concept was that the selectivity was changed by changing the mesh size in the escape window (Madsen, 2002). This was expected to make stepwise changes easier and reduce costs compared to changes of the whole gear. The original test of the Bacoma codend indicated that the SF was relatively constant when mesh size was changed in the window but not in the rest of the codend (Madsen, 2002). A further advantage of the Bacoma codend was that it is more flexible and easier to handle than a full square mesh codend, and furthermore, a window can be installed very easily in an existing trawl (Madsen et al., 2002).

A Bacoma codend with the same mesh size (around 122 mm) in the window and the codend was tested in the semi pelagic cod fishery by Danish and Swedish vessels (Madsen et al., 2010). The selection factor was comparable to the earlier experiments (Table 3.1) where the mesh size in the codend was kept at 105 mm (Madsen et al., 2002). It was found that the selectivity of the Bacoma codend was not influenced by the codend catch weight which was the case for the standard codend and the codend with New Danish windows (Madsen et al., 2010).

The estimated SF of a Bacoma window codend, constructed in accordance with regulations, in a more recent German experiment (Herrmann et al., submitted) was comparable to previous with estimates from Bacoma 120mm/105mm-codends (Table 3.2). In this experiment it was found that a substantial proportion (32%) of the cod escapes from a Bacoma codend during haul-back (Herrmann et al., 2013), which is the limited period when the trawl is hauled from the sea floor until it is on the deck. This indicates that a large proportion of the cod don’t make escape attempts during towing. The L50 of the currently used Bacoma codend have also been calculated for plaice and flounder (24.0 cm, and 22.9 cm respectively; Herrmann et al., submitted).

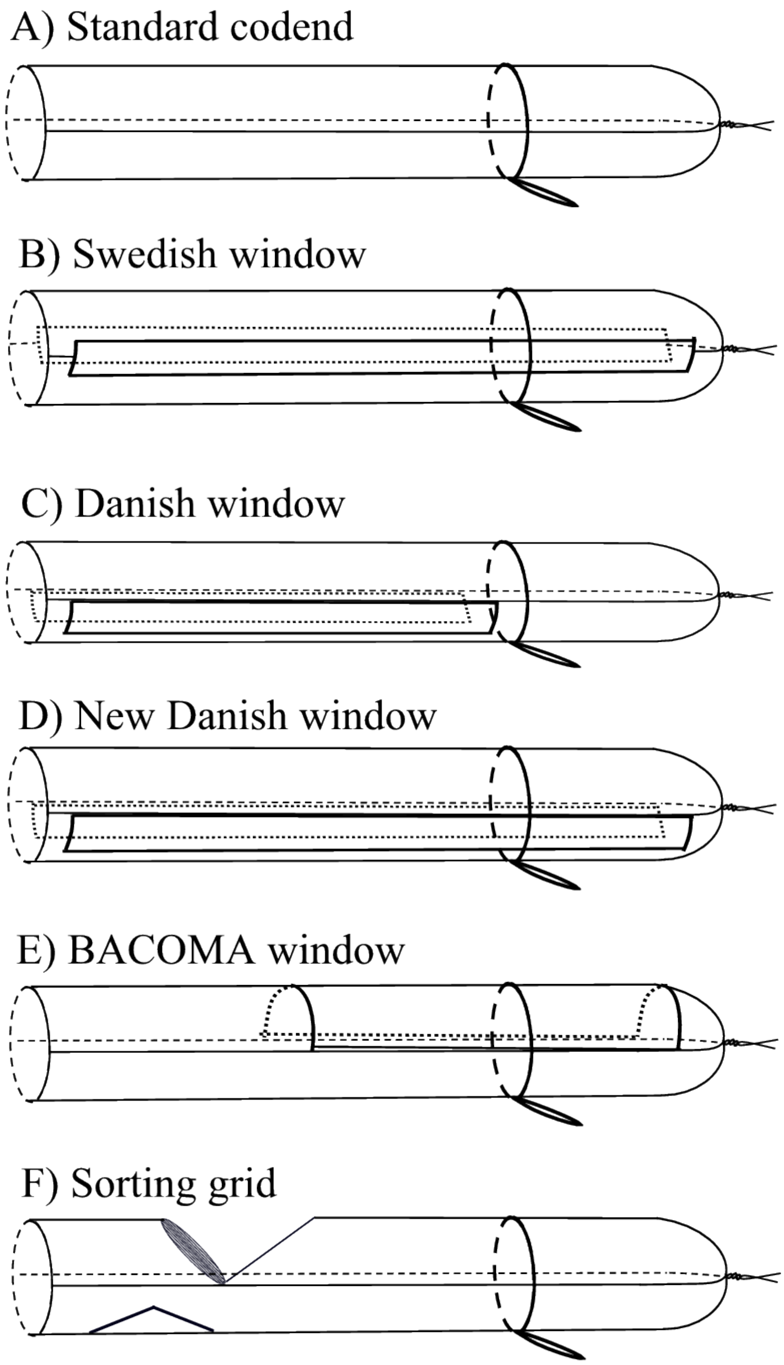


Figure 3.2. Different selective codends

Table 3.1. Estimates of L50 and SR of cod for different codends relevant to legislation in the period from 1989 until today. SF (L50/mesh size) is the selection factor and SRA selection ratio (SR/L50).

Codend type	Mesh size	*L50* (cm)	*SR* (cm)	SF	SRA
Estimates before 2007					
[1]Standard (sPA)	100 mm	32.8	7.0	3.28	0.213
[1]Standard (4 mm dPE)	105 mm	28.6	8.1	2.72	0.283
[1]Standard (4 mm dPE)	120 mm	35.6	9.3	2.97	0.261
[1]Danish window	W 105 mm; ST 105 mm	31.6	6.8	3.01	0.215
[1]Swedish window	W 105 mm; ST 105 mm	37.3	6.4	3.55	0.172
[1]New Danish window	W 105 mm; ST 105 mm	33.1	7.9	3.15	0.239
[1]Standard (4 mm dPE)	130 mm	40.3	10.0	3.10	0.248
[1]PA Standard (sPA)	125 mm	41.0	8.8	3.28	0.215
[1]Standard (4 mm dPE)	140 mm	44.9	10.8	3.21	0.241
[1]Bacoma window	W 120 mm; ST 105 mm	45.5	6.7	3.79	0.147
[1]Bacoma window	W 110 mm; ST 105 mm	41.7	6.1	3.79	0.146
[1]T90 (net unspecified)	110 mm	39.8	6.7	3.62	0.168
[1]T90 (net unspecified)	120 mm	43.4	7.3	3.62	0.168
Estimates after 2007					
[2]T90 (5 mm sPE; 50 meshes)	124.1 mm	42.6	5.2	3.43	0.121
[2]Bacoma window	W 125.7 mm; ST 104.5 mm	46.3	7.1	3.68	0.152
[3]Bacoma window	W 127.1 mm; ST 127.3 mm	49.3	5.13	3.88	0.104
[3]Bacoma window	W 127.1 mm; ST 127.3 mm	50.3	7.85	3.96	0.156
[3]New Danish window	W 127.5 mm; ST 127.0 mm	48.2*	7.16	3.80	0.149
[3]New Danish window	W 127.5 mm; ST 127.0 mm	50.3	6.15*	3.96	0.122
[3]Standard (4 mm dPE)	ST 141.8 mm	49.3	7.16	3.48	0.145
[3]Standard (4 mm dPE)	ST 141.8 mm	49.3*	7.85	3.48	0.159
[4]Standard (5 mm sPE; 92 meshes)	ST 114.7 mm	34.2	5.8	2.98	0.170
[4]Standard (5 mm sPE; 44 meshes)	114.4 mm	39.3	5.6	3.44	0.142
[4]T90 (5 mm sPE; 91 meshes)	114.3 mm	38.6	4.9	3.38	0.127
[4]T90 (5 mm sPE; 46 meshes)	114.5 mm	42.0	4.9	3.67	0.117

W = window mesh size; ST = standard diamond mesh netting; [1]Model based on available data set (Madsen et al., 2007); [2]Herrmann et al. (submitted); [3]Madsen et al. (2010); [4]Wienbeck et al., 2011; *Codend catch weight set at 400 kg, since estimate is catch dependant.

T90 codend

T90 netting has been the focus of increased scientific interest in recent years (ICES 2010, 2011), and it was implemented in legislation for the Baltic Sea cod fishery in 2006 (Figure 3.1; Madsen 2007). In T90 codends, the standard (T0) diamond mesh netting is turned 90 degrees (Figure 3.3) which is expected to improve size selective properties of some species compared to traditional codends made of the same netting (Figure 3.3). In the traditional standard netting orientation, the mesh resistance to opening tends to close the meshes during towing. Turning the netting 90 degrees reverses this mechanism, which provides a more open mesh under pull that might allow cod to escape. The netting knot size, defined by the knot type and twine characteristics, may also contribute to the benefits provided by turning the netting by 90 degrees (Herrmann et al., 2007). The T90 codend is a very simple way to improve the size selectivity of the fishing gear, as standard conventional netting can be used. Furthermore, the T90 codend retains flexibility compared to the Bacoma codend where the square meshes are fully stretched and thus more sensitive to drag forces. T90 codends were initially tested in Polish (Moderhak, 1997; Moderhak, 1999; Moderhak, 2000a; Moderhak, 2000b) and German experiments (Wienbeck and Dahm, 2000). Results from these experiments are included in Table 3.1 (values before 2007).

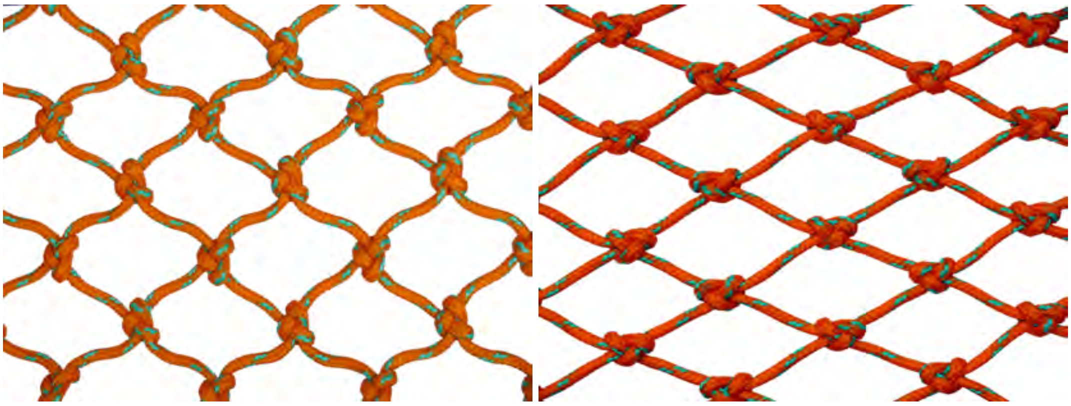


Figure 3.3. Left: diamond mesh netting in T90-orientation; Right: diamond mesh netting in T90-orientation.

A theoretical simulation-based study (Herrmann et al., 2007) estimated that a 50% reduction in codend circumference, which was introduced in the Baltic Sea when the T90 codend was implemented in legislation, would contribute considerably to an overall increase of L50 (50% retention length) when simultaneously turning the meshes by 90°. This finding suggests that when evaluating the effect of T90 meshes on selectivity, it is important that other codend design parameters are not changed simultaneously. Results of a recent experiment (Wienbeck et al., 2011) are presented in Table 3.1. Here, the theoretical predictions were confirmed. The L50 for the T90 netting is higher than for the standard netting. It was found that the L50 increased with decreasing number of meshes in circumference. The SF of the T90 codend with 46 meshes in circumference is comparable to some of the SF estimates of the Bacoma codends. The L50 of plaice and flounder is estimated to 23.7 cm and 23.6 cm respectively and not statistical significantly different from the L50 of a Bacoma codend. The proportion of cod, plaice and flounder escaping during haul-back is estimated to 40%, 26% and 29% respectively (Herrmann et al., submitted). Although 8% more cod escaped during haul-back compared to the Bacoma codend, this difference was not statistically significantly.

Grids

The flexibility of netting material results in non-constant selective properties of the netting and hence of the codend. This often results in relatively high selection range values, which are problematic when aiming for sharp selection to avoid discards and to avoid commercial loss at the same time. A selective device with stable selective properties could theoretically improve the selectivity of the gear.

Sorting grids (Figure 3.2D) were first developed back in the 1980s (Larsen and Isaksen, 1993) and were implemented in the Barents Sea cod fishery in 1997 (Kvamme and Isaksen, 2004). The sorting grid codend will retain larger cod that are not able to penetrate the bars. Three different types of sorting grids are used in the Barent Sea today.

Kvamme and Isaksen found a similar SR for the grid and a codend used in the Barents Sea. Neither did Grimaldo et al. (2008), Jørgensen et al. (2006) nor Graham et al. (2004) find any indications of a difference in SR range of the grid compared to a diamond mesh codend or a codend fitted with an escape window (Graham et al., 2004; Grimaldo et al., 2008). Sistiaga et al. (2010) estimated the probability of cod getting in contact with the grid to be 75%. Sistiaga et al. (2008) found an increase in L50 from a 56.1 cm to 73.3 cm when increasing bar distance from 55 to 80 mm but also an increasing SR. In another experiment it was, however, found that more cod escaped from a grid at depth during towing compared to a diamond mesh codend (Grimaldo et. al., 2009).

A disadvantage about the sorting grid is the handling. This will particularly be the case in the Baltic Sea because relatively small vessels are used compared to the Barent Sea.

Gears used commercially

Information concerning which gears were used from 2000 until 2010 were collected through the fishermen questionnaires (see full questionnaire in Appendix 1). This information is provided in Table 3.2 below. The different codend types are illustrated in Figure 3.1. *The "Swedish" and "Danish" window were included in the legislation until 2002 (Madsen 2007), the standard codend was in the legislation until 2004, the Bacoma codend from 2002 and the T90 codend from 2006. The Bacoma codend is by far the codend that has been used by the greatest number of vessels. However, it should be borne in mind that it is also the codend that has been in the legislation longest.*

Table 3.2. Answers from the questionnaires concerning which gears were used in year 2000-2010.

Country	Standard codend	Swedish window	Danish window	Bacoma window	T90 codend	Don't know
SE	2	7	3	22	5	0
DE	2	1	0	6	3	2
PO	2	0	0	6	3	3
DK	3	0	7	22	0	0
Total	9	8	10	56	11	5

Table 3.3 indicates which codends are used today by the fishermen who replied to the project questionnaire. In total the Bacoma codend is used about twice as much compared to the T90 codend.

Table 3.3. Answers from the questionnaires concerning which codends (Bacoma or T90) are used today and which trawl rigs (single or twin).

Country	Bacoma-single trawl	Bacoma-twin trawl	T90-single trawl	T90-twin trawl
SE	24	4	7	0
DE	7	1	4	3
PO	11	0	4	0
DK	13	7	9	4
Total	55	12	24	7

The fishermen questionnaires indicate that both the T90 and the Bacoma codend are commercially used by the fishermen today.

The comments from the fishermen (see Appendix 1) indicated that some fishermen find that the selectivity of both codends is not good enough and some that the selectivity is too high. It is likely that the area and the way the fishery is conducted are very influential on this opinion.

Unaccounted mortality

For improvement of fishing gear selectivity to make any sense, it is important that escapees survive the mesh penetration, as this can cause stress and physiological injuries. Experiments have been conducted on cod in different areas to assess this issue. Table 3.4 presents results from such experiments. This table illustrates that the survival of cod escaping through codend meshes during towing is generally high. There was no mortality observed during the two experiments conducted in other areas, whereas some mortality was observed in the experiments conducted in the Baltic Sea.

Very low mortality rates were found in the first experiments conducted (Suuronen et al., 1996). Higher mortality was found in the later experiments (Suuronen et al., 2005). This was most likely explained by the exceptionally high water temperature at the cage site, which would not be expected at the fishing grounds. No clear relationship was found between fish length and mortality (Suuronen et al., 2005), fish length and degree of skin injury (Suuronen et al., 1996; Suuronen et al., 2005) and skin injury and codend type (Suuronen et al., 2005).

For cod, in particular escapement during the haul back phase is problematic. Since cod have no connection between their swim bladder and gut (physoclist), they may suffer from decompression when not able to compensate immediately. A Scottish experiment suggests a higher mortality for haddock and whiting escaping a trawl during haul-back than when escaping during towing (Breen et al., 2007). However, Soldal and Isaksen (1993) only found 1 % mortality for cod escaping at the surface from a Danish seine. More work is needed to clarify this further. Also the mortality of fish that have been in contact with gill nets needs to be investigated.

Table 3.4. Mortality after escape through trawl codends during towing.

Area and gear	Mortality	Reference
Barents Sea		
Shrimp grid	0%	Soldal and Engås (1997)
Shrimp grid	0%	
Baltic Sea		
Codend with 95 mm window	Cod: 2.5%	Suuronen et al. (1996b)
Codend with 95 mm window	Cod: 0%	
Codend with 105 mm window	Cod: 13%	Suuronen et al. (2005)
120 mm codend	Cod: 15%	
Codend with 105 mm window	Cod: 2%	
West Atlantic		
120 mm codend	Cod: 0%	DeAlteris and Reifstick (1993)

Whereas selectivity of cod is assumed to be not problematic for gill nets, ghost fishing could be problematic. Ghost fishing can be defined by: mortality of fish and other species that takes place after all control of fishing gear is lost by a fisher (Brown and Macfadyen, 2007). In this context the problem is related to set nets which are made of non-biodegradable synthetic fibres having the potential to continue fishing for a long time after being lost. According to Tschernij and Larsson (2003) around 160 km of gill nets are lost per year by Swedish fishermen alone, mainly in the cod fishery. However, some of these nets are retrieved by trawlers. The catching efficiency could be expressed by an exponential decreasing curve illustrated by Figure 3..

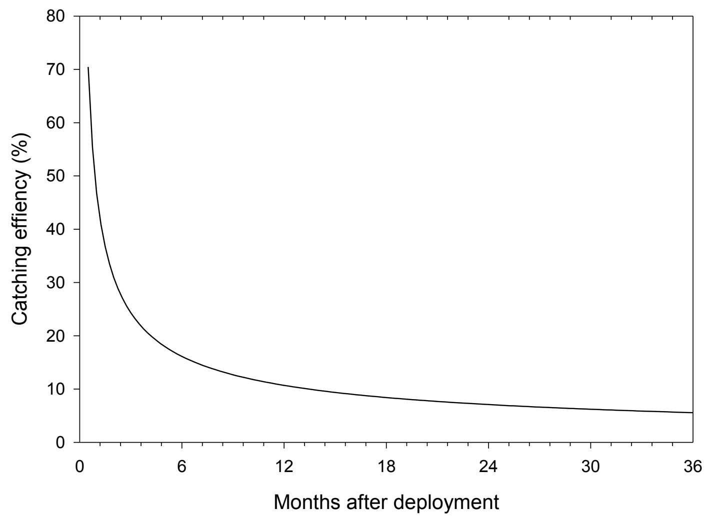


Figure 3.4. Catching efficiency as a function of months after deployment. Figure from Madsen (2007).

Improving species selectivity in the flatfish fishery

Flatfish species are characterized by their extreme lateral body compression which clearly differentiates them from roundfish species such as cod. These morphological differences play a major role on the size selection process in codend meshes, mainly related on how close the mesh geometry fits to a given fish morphological dimension. For roundfish the most important dimension affecting escapement probability is the body girth, while for flatfish this probability is mainly conditioned by the body width (Fonteyne and M'Rabet, 1992), therefore, gears designed under the perspective of one of these fish groups might have counteracting effects on the selectivity for the other. As an example, It has been proved that using square geometry increase roundfish escapement likelihood, while diamond shape (standard T0 meshes) fits better for flatfishes (Guijarro and Massutí, 2006; Fonteyne and M'Rabet, 1992; Walsh et al., 1992). Given such counteracting process, it can be concluded that the improvement of flatfish selectivity in Baltic Sea might not be linked with the successive improvements implemented for the Baltic cod.

The focus of technical measures in the Baltic Sea was on codend size selectivity for cod in Baltic cod trawl fishery. For fisheries not targeting cod, the avoidance of cod in general is desirable. Whereas the need to avoid cod bycatches is limited under current regulations, the demand for such solution will increase when the landing obligation comes into force.

Flatfish also remain in the lower part when entering the trawl (Main and Sangster, 1985; Thomsen, 1993; Bublitz, 1996; Ryer, 2008) but it has also been observed that they can also rise into the middle of the gear further down in the trawl (Thomsen, 1993; Krag et al., 2009a, 2009b; Krag et al., 2010).

Selective flatfish trawls have been developed and tested for the flounder fishery (Madsen et al., 2006). The experiment was based on a concept of allowing cod to escape upwards either through large meshes (Madsen et al., 2006) or by removing the main part of the top panel (Mieske, 2008). In some experiments (Madsen et al., 2006), the selective trawls have been combined with square meshes codends to also improve size selectivity for cod (Tschernij et al., 1996; Madsen et al., 2002) but these were less selective for flatfish because of the flat shape of these fish. The trawl tested by Madsen et al. (2006) was designed with a small vertical opening, large meshes at the top panel (400 mm) and an escape panel with 117 mm square meshes in the codend. The bycatch of cod per kg of caught flounder (above MLS) was reduced by 85% when a chain mat was used to increase flounder catches and 67% in a second experiment without the chain mat (Madsen et al., 2006). Also the experiments by Mieske (2008) demonstrated a substantial reduction of the cod catch by 60-80% without reducing the catch of flounder. Similar trawl design concepts have also been developed and tested in other fisheries and areas. Beam trawls have been modified by removing large sections of netting behind the beam or replacing them with sections of large meshes. Marlen (1993) found catches of cod to be reduced by up to 48% without loss of plaice, but some reduction in the sole catch. New experiments with large mesh top panels in beam trawls showed a reduction in cod and virtually no losses in flatfish catches (Marlen, 2003). Thomsen (1993) modified a trawl by reducing the height of the trawl, the forward part of the top panel and inserted large meshes in the middle part of the top panel. A reduction of cod was found and no loss of flatfish. Chosid et al. (2008) tested a similar concept and also found a reduction in cod catches. Catches of flatfish and other species were also reduced but with diurnal differences, making catches of target species more acceptable during day.

Gill nets

Gillnets are widely used in the artisanal fishery throughout the Baltic. At least regarding fish, gillnets are assumed to be selective (problems potentially occur for birds and marine mammals).

Twine thickness (Holst et al., 2002; Wileman et al., 2000), hanging ratio (Wileman et al., 2000) (length of the mounted net as a fraction of the stretched length of the netting) and season (Wileman et al., 2000) have relatively little effect upon the size selectivity of Baltic cod gill nets.

The parameters provided in Table 3.5 are estimated for Baltic gill nets with 50% hanging ratio, and a twine thickness of 1.5*4 (a Japanese numbering system indicating that there were 4 threads of number 1.5 monofilament thread) , which is the twine thickness used by most gill net fishermen in Denmark and Sweden fishing in the Baltic Sea (Wileman et al., 2000). Parameters are also provided for a thicker twine (1.5*6) and lower hanging ratio.

Gill net selection curves for Baltic cod gill nets can be described by a bi-normal selection curves (Wileman et al., 2000; Holst et al., 2000; Holst et al., 2002):

$$R(L) = \exp^{-\frac{(L - a_1 * MS)^2}{2(b_1 * MS)^2}} + \omega * \exp^{-\frac{(L - a_2 * MS)^2}{2(b_2 * MS)^2}}$$

where a1 and b1 describe the location and spread of the primary mode and a2 and b2 describe the location and spread of the secondary mode. The reason for the bi-normal appearance is that the majority of cod are gilled, while larger (relative to the mesh size) individuals are often retained by maxillary enmeshing or otherwise entangled (Wileman et al., 2000; Holst et al., 2002).

Table 3.5. Gill net selectivity parameters for cod from Wileman et al. (2000) referring to a bi-normal selection curve.

Thread type	Hanging ratio	a_1	b_1	a_2	b_2	ω
1.5*4	50%	4.45	0.265	5.92	1.23	0.137
1.5*4	40%	4.51	0.265	5.92	1.23	0.137
1.5*6	50%	4.35	0.265	5.92	0.72	0.137

The corresponding selection curves are shown in Figure 3.. This Figure demonstrates that even though there is significant difference in the selectivity parameters it is relatively limited from a management point of view.

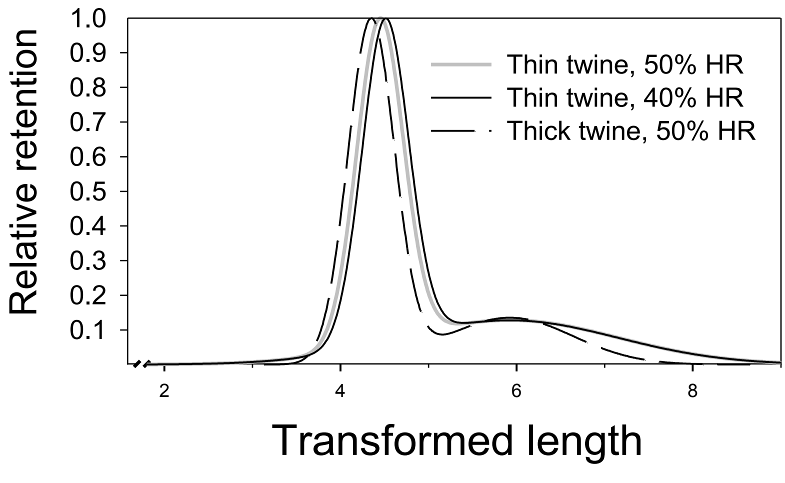


Figure 3.5. Gill net selection curves by using parameters from Table 3.5. The thick line indicates the 1.5*4 twine and the thin line the 1.5*6 twine. HR indicates hanging ratio. Transformed length is length/mesh size. Figure from Madsen (2007).

Discussion and conclusion

Several investigations to improve selectivity in Baltic fisheries were conducted during the last years. Most of the investigations and technical measures focus on the improvement of the size selectivity of cod in the Baltic cod trawl fishery.

Estimates of the selectivity in the Bacoma and T90 codend, as defined in legislation, indicate a relatively high SF and hence overall good selectivity for cod. For the Bacoma codend it is also found that the selectivity is stable at higher codend catches. Increasing the length of the Bacoma panel in legislation might have solved the problem of reduced selectivity during bulk catches. The main concern regarding the current legal Bacoma design is the unbalance between the selective properties between the 120 mm square mesh panel and the 105 mm diamond meshes in lower panel. It has been demonstrated that cod would try to escape through the top panel as well as through the lower panel (Frandsen et al., 2010). If cod only make few escape attempts, individuals might fail if they do this in the wrong direction. This affects the selectivity of the entire codend, which is a combination of the selective properties of both nettings. Dual selection is not desirable as it can lead to a high selection range, resulting in higher discard rates or losses of legal size cod. This potential dual selection problem can be solved by either making a full square mesh codend or increasing the mesh size of the diamond meshes. A full square mesh codend might give practical handling problems because of reduced flexibility and potentially reduced selectivity for flatfish.

The current technical regulations in Baltic sea trawl fisheries allow the fishers to use two different codend alternatives -The T90 and the Bacoma codend- (EU 686/2010), both designed under a cod-selection perspective, aiming to increase the number of meshes opened in square shape during the towing process. From these codends, only the lower panel of Bacoma codend uses diamond netting, which fits better to flatfish morphology, however, the current 105mm mesh present limited selective properties these species, as showed in Hermann et al. (2013), where the Bacoma L50 for flounder was estimated to be below 25cm, an insufficient value considering that flatfish discard behaviour is affected by market preferences rather than MLS.

From the current status it can be outlined two different approaches in order to improve flatfish selectivity in the Baltic cod fishery: i) the increment of mesh size of the Bacoma diamond netting, or ii) to adopt technological strateges accounting for the specific flatfish morphology and behaviour.

The mesh opening of the T90 codend is not stable. This instability results in different selectivity properties influenced by variable factors like codend weight. This might also contribute to reduced escape during towing and increased escape during haul-back. Furthermore twine characteristics, like twine thickness and single versus double twine, will affect the mesh opening and hence the selectivity. This is not addressed in the legislation. Improved knowledge about the influence of twine properties (single or double twine and thickness of the twine) is therefore necessary to decrease variability in size selection of T90 cod ends. Thus, one simple way to mitigate potential discard of cod would be to optimize the twine specifications for legal T90 codends in the Baltic Sea, based on experimental work.

There is a high proportion of cod, plaice and flounder that first escapes during the haul-back process. This is the case both for the Bacoma codend and the T90 codend (Herrmann et al., in press). A considerable haul-back escape is also observed in other cod fisheries (Grimaldo et al., 2009; Madsen et al., 2012). Any late escape will increase the possibility of additional unaccounted mortality. When cod first escape during the haul-back rather than during towing they will most likely be exposed to more stress and physical injury. Cod will suffer from decompression and at the surface they will be subjected to sea bird predation. Some of the escape will occur in the beginning of the haul-back phase where the probability of survival is likely to be higher than for late escape. The haul-back escape is likely to be influenced by several factors like haul-back duration, sea state and codend catch weight (Madsen et al., 2008). This suggests that it is important to develop selective fishing gears that are better to let fish escape immediately when entering the codend during towing. Potential solutions are scaring devices and improved selective properties during towing. Also a reduced speed in limited periods might provide increased escape opportunities.

Selective devices like grids can be difficult to handle, particularly because smaller vessels are often used in the Baltic Sea. There are no clear indications of improved selective properties of grids. Grids might, however, increase escape during towing since the fish are guided towards the grid ensuring a high contact probability during towing. Furthermore they might be able to improve species separation by reducing flatfish catches.

The fishermen questionnaires indicate that some fishermen prefer the T90 and some the Bacoma codend. Thus, having two rather different codend types in the legislation provides the opportunity for the fishermen to choose what fits best.

Different technical devices relevant to this project and their expected pros and cons (pro et contra) are summarised in Table 3.6.

Gill nets are relatively selective and it is relatively easy to adjust size selectivity by adjusting the mesh sizes, since technical parameters don't influence the selectivity very much, as opposed to trawls.

Table 3.6. Expected pros (+) and cons (-) for relevant technical solutions for trawl codends.

Codend	Expected pros and cons
Bacoma	+: Widely used; Simple device; Possibly to improve flatfish selectivity. -: Expensive netting; Difficult to repair.
T90	+: Widely used; Simple device. -: Mesh opening depending on drag, performance could change after use and depends on twine characteristics.
Full square mesh	+: Improved cod selectivity -: Low selectivity of flatfish; Price; No flexibility in netting; Difficult to repair.
Grid devices	+: Successfully used in other areas; Bars can be used to improve flatfish selectivity; Might increase contact probability during towing -: Difficult to handle and repair; Price

3.2 Flumetank trials

Back ground for test codend

Flume tank tests were conducted prior to the sea trials to obtain documentation for demonstration, inspection and measurements of the performance.

Based on Fishermen interviews, the workshop in Karlskrona and consultations with the industry, it was decided to test seven different codends prior to the sea trials. Seven different codends were constructed and details are provided in Table 3.7. Pictures of all codends during flumetank tests are provided in Figure 3.6. All codend are of relevance to the Baltic Sea cod fishery either by being used in the past, today or being potential for implementation in the future. Background for codend constructions were: 1) standard codend, which was specified for use in legislation in the Baltic Sea until 2004 (Madsen, 2007). Standard diamond mesh codends are used in many European fisheries; 2) T90 codend, the T90 (netting turned 90°) codend is specified in the legislation for the Baltic Sea (Madsen, 2007) and widely used today (see section 3.2); 3) Bacoma codend, which is specified in the legislation and widely used in the Baltic; 4) Bacoma T0, which is a Bacoma codend but with the window square meshes in traditional direction (T0) and a rope in the selvedges to keep the net panel with a fixed length. This codend was constructed by a local net maker (Nexø vod) to overcome the problem with mesh distortion of observed in the window square meshes of the Bacoma codend; 5) a two panel codend made of full square meshes that might provide a better selectivity for roundfish than the presently used Bacoma codend having diamond meshes in the lower panel; 6) a four panel codend made in full square meshes. The two-panel square mesh codend has been criticised in the past for being difficult to handle when taking the catch on board. To meet this problem the four panel codend was constructed.

Technical specifications on test codends

Technical specifications of the tested codends are provided in Table 3.7. It was aimed at standardise as much as possible when constructing the codends. The codends were constructed having the same overall stretched length. The mesh size of the diamond mesh netting was 25 mm higher than what is defined by present legislation being in order to standardise constructions and to use mesh sizes that are likely to be used in the future. The diamond mesh netting was made of 4 mm green polyethylene (PE) double twine netting with an inside nominal mesh size of 130 mm. This is the most used material by the Baltic cod trawler fleet.

For square mesh panels black PE (polyethylene) single twine netting with a twine thickness of 4.9 mm and breaking strength of 330 kg were used. In this netting the twine threads are continuous in the all bars direction making it very strong and of stable mesh configuration when used as square mesh netting. This twine product is used for the major part of square mesh windows in the Baltic Sea where the legislation specifies use of single knotless twine with a minimum thickness of 4.9 mm. It is thought that traditional double twine netting material is not well suited for windows because the double twines tend to separate, reducing the opening of the meshes and not giving fish an optimal chance of escape (Madsen et al., 2002). Another problem observed when using conventional netting in square mesh windows is knot slippage, which leads to a high degree of uneven mesh sizes and shapes (Madsen et al., 2002). This could particularly be a problem when the window extends behind the lifting strop where the loading is very high when hauling the catch.

Table 3.7. Codend specifications. Meshes indicate the number in circumference.

Codend	Top panel		Bottom panel	
	Netting	Meshes	Netting	Meshes
Standard	4mmDB–D130mm	46	4mmDB–D130mm	46
T90	4mmDB–D130mm	46	4mmDB–D130mm	46
Bacoma	4.9mmSB–SQ120mm	23	4mmDB–D130mm	46
Square 2P	4.9mmSB–SQ120mm	23	4.9mmSB–SQ120mm	23
Square 4P	*4.9mmSB–SQ120mm	12	4.9mmSB–SQ120mm	12
Bacoma T0	4.9mmSB–SQ120mm	23	4mmDB–D130mm	46

*Including side panels; D: diamond meshes; DB: double twine; SQ: square meshes; SB: single braided twine.

The net panels of diamond mesh netting were constructed having a width of 46 open meshes in each net panel giving a codend circumference of 92 open meshes and 4 meshes enclosed in each of the two selvedges. This one of the most common ways to produce commercial codends for Baltic Sea cod fishery. The legislation specifies that the maximum number of open meshes in circumference is 100. The length of the diamond mesh netting sections was 49.5 meshes. All codends were ended by three rows of diamond meshes. This ensures a uniform and strong opening of the codend where the codline is attached. This construction is allowed by legislation and is used by the majority of the trawlers.

Results

The codends were tested with a simulated catch of 500 kg (plastic bags with water) in a flumetank in Hirtshals (Denmark). The maximum flow of this flumetank is 0.9 m/s, which is equivalent to a towing speed of 1.8 knots.

From Figure 3.6 it can be observed that the diameter of the standard codend, the T90 codend and the lower panels of the Bacoma codends decrease going in forward direction starting at the beginning of the catch build up (around the lifting strops). The consequence is that the opening degree of the meshes will decrease. If the catch increases further from the test level the mesh opening in front of the catch, where the fish is most likely to escape will be more closed. This would likely decrease selectivity of cod but increase selectivity of flatfish.

The circumference of the T90 codend is larger in the beginning of the codend than for the standard diamond mesh codend and consequently the mesh will be more open.

The square meshes of the TO Bacoma panel stays in their configuration and the panel is slack. No problems of the configuration of the two panels and four-panel codend were observed. The circumference of the codend in the catch region is lower compared to the other codends. As a consequence the codend will be filled up faster. At around 1.5 tonnes the catch will end in the area in front of the codend and selectivity will depend on the meshes of this region and the square meshes don’t have any effect.

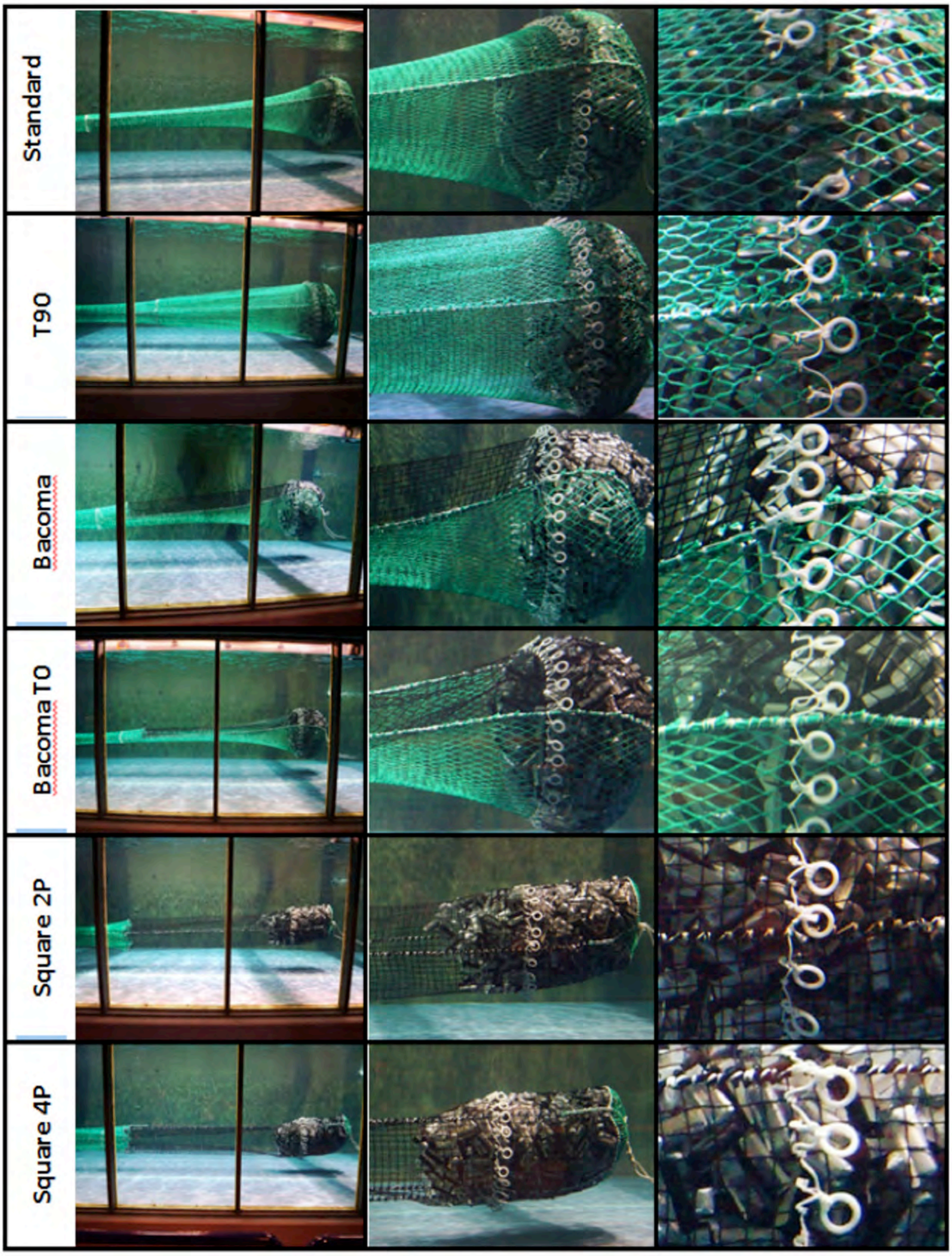


Figure 3.6. Codends tested during flume tank sessions.

The drag of the codends were measured at a water flow (towing speed) of 1.8 kts and the results are presented in Table 3.8. Theoretical estimates were made for higher and lower water flows assuming the catch distribution to be unchanged. The drag is lowest for the two codends made of full square mesh panels. The reason is that there is no flexibility in the square meshes and the catch will move forward rather increasing the codend circumference. The difference in drag will increase with increased water flow.

Table 3.8. The measured drag at 1.8 kts water flow with 95% confidence limits in brackets and theoretical estimates of drag at different flows (towing speeds).

Flow (kts)	Standard	T90	Bacoma	Bacoma T0	Square 2P	Square 4P
1.5	83	122	67	64	30	27
1.8 (measured)	119 (±0.23)	176 (±0.19)	95.9 (±0.20)	92.0 (±0.30)	43.1 (±0.09)	39.2 (±0.05)
2.0	147	217	118	114	53	48
2.5	230	340	185	177	83	76
3.0	331	489	266	256	120	109
3.5	450	665	363	348	163	148

Discussion and conclusion

The codend constructions and the net materials did not indicate any concerns during the flume tank tests. The codends were however newly produced and codends used during commercial fishing might show another performance. A problem experienced by the fishermen and netmakers is that the mesh opening in the Bacoma window is distorted after a while because of the high tension combined with no flexibility in the square mesh netting. The Bacoma T0 codend might be a way to solve this problem. Additionally it might be possible to use traditional netting materials that are cheaper, more easily accessible and easier to repair than the single knotless twine used today. Use under commercial conditions should clarify this further.

The circumference T90 codend is higher than for the standard codend. Hence the mesh will be more open. However, the codend circumference decreases when moving forward and the mesh opening will decrease. The mesh opening is hence not stable and the opening degree will depend on catch rates and position in the codend.

The two codends made of full square meshes will be faster filled up than codend construction including diamond meshes. We estimate that this will happen with catches around 1.5 tonnes. The consequence will be that the selectivity will take place ahead of the codend and dependent on the selectivity of the meshes in this region. To avoid this problem the codend should be longer or have more meshes in circumference. We did not detect any marked differences in the performance comparing the two panels with the four-panel codend. The drag resistance is lower in the two full square mesh codends compared to the other codends.

The dynamics of the codends might with higher or lower catch rates than used in this these flumetank trials. Furthermore, no lifting strops were used in these experiments. The lifting strop can influence the codend and hence the mesh-opening if the strop limits the codend circumference in increasing further.

3.3 Test of suggested gear modification onboard commercial vessels

Decisions on further progress

It was decided to focus on the trawl fishery because the majority of the discard is from this fishery. Furthermore the technical review identifies that gill nets are relative selective and it is relative easy to adjust the size selectivity by adjusting the mesh sizes. It was decided that further work in gill net fishery was not necessary and focus should be on improving selectivity in the trawl fishery.

Based on Fishermen interviews, discard analysis, the workshop in Karlskrona, consultations with the industry, flume tank test and preliminary tests from a research vessel, it was finally decided to test four different selective devices from commercial vessels:

1) A T90 codend with 120 mm mesh size made by 8 mm single twine (named: T90 120 s8). The reason for testing this codend is that the T90 codend is widely used in the Baltic Sea and generally found acceptable by the fishing industry. Furthermore, recent research (Annex 4) indicates that it is possibly to improve selectivity further by decreasing the selection range. This codend was tested from a Swedish commercial vessel.

2) A Bacoma codend with the mesh size increased from 105 mm to 130 mm diamond meshes in the lower panel (named: Bacoma 120/130). The reason for testing this codend is that the Bacoma codend is widely used in the Baltic Sea and generally found acceptable by the fishing industry. Increased mesh size in the lower panel will increase selectivity of cod and flatfish and the selectivity of cod will be in better accordance with the selectivity of the 120 square meshes in the top panel. This codend was tested from a Danish commercial vessel.

3) A full square mesh codend with 120 mm meshes (named: square mesh 120). The lower panel will be made similar to the 120 mm square mesh panel used in the top panel of the Bacoma codend. This codend is expected to improve the selectivity substantially of cod in the lower panel, compared to the 105 mm diamond mesh used today. This codend was tested from a Danish commercial vessel.

4) An innovative grid design (named: Freswind Bacoma 120/105). A grid device was suggested to be tested by fishermen at the Karlskrona workshop and grid devices are successfully used in cod fisheries in other areas. The grid design is expected to reduce the unwanted bycatch of flatfish species (particularly discard of flounder), as well as to increase cod selectivity by avoiding blocking of the meshes. This codend was tested from a German commercial vessel.

Methodology for conducting the sea trials

The sea trials were conducted by commercial twin trawlers with the aim of performing a direct catch comparison between a reference trawl (as reference for the currently gears used in the Baltic trawl fishery) and a test trawl fishing simultaneously. Catch comparison experiments aim to produce statistically sound estimations of the relative difference in catch proportions between the test and the reference trawls. Although, catch comparison is the general methodology used in Bottom Trawl Surveys calibrations, it also has emerged as an alternative tool in gear technology studies in recent times for several reasons:

- It does not require extra-rigging (cover codends), or non-selective codends attached to the gear during the data collection, which is seen as a clear advantage during the practical implementation of the experimental design onboard commercial vessels.

- The workflow onboard is similar to the commercial fishing activity.

- In contrast to the covered codend methodology, the number of compartments to be sampled is reduced to one per gear tested.

- The results from the comparison can be better understood by fishermen than the outputs from the selectivity models (catch more than/less than).

The test and reference trawls had identical commercial specifications, with the only difference that the test gear mounted the selective devices tested in the project. The Bacoma codend specified by the legislation (120 mm square meshes in the top panel and 105 mm diamond meshes in the lower panel) was fitted as reference trawl in all sea trials. The reason is that this is likely the most commercially used codend since year 2002 (see section 3.1). Reference and test codend were swapped from side to side in order to avoid potential side effects during the trials.

The catch comparison experimental design is not directly focused on studying the size selection process, but the total catch ratio between the test and the reference codend. Let n_t be the number of fish caught in the test gear, n_r the number of individuals caught in the reference gear, and n_+ the global catch. Let

$$\mathrm{p} = \frac{n_t}{n_+}$$

Be the catch ratio in *test* codend. The catch ratio (*p*) only can take values between 0 and 1. If p~0.5, then it is assumed equal fishing efficiency for *test* and *reference* gear, p<0.5 means lower efficiency in test and the opposite when p>0.5. Based on theory statistics, we assume that the number of flounders in the test codend follow a binomial distribution,

$$\mathrm{n}_t \sim Binom(n_+, p)$$

Because we are interested on the effect of length size in the catch ratio, the earlier can be derived to

$$\mathrm{n}_t(l) \sim Binom(n_+(l), p(l))$$

Being *l* the fish length size. The fact that the response only can take values between 0 and 1 violates the basic assumptions of standard regression tools, therefore to estimate the $p(l)$ curve we use regression tools specially developed to deal with binary data. The underlying approach is to transform the response into a linear form $[-\infty, \infty]$. In this case, we use herein the *logit* link function:

$$Logit(l) = lnOdds(l) = ln\frac{p(l)}{1 - p(l)}$$

The classic logistic models perform a linear approximation of the effect of *l* on the test codend catch rate:

$$p(l) = \frac{\exp\left(\beta_0 + \beta_1 l\right)}{1 + \exp\left(\beta_0 + \beta_1 l\right)}$$

To allow certain degree of smoothness of the effect of *l* on the catch rate, penalized regression splines (Wood, 2006) instead of a full parametric estimation:

$$p(l) = \frac{\exp(\beta_0 + f_1 l)}{1 + \exp(\beta_0 + f_1 l)}$$

The resulting *p(l)* is therefore the relative catchability curve of fish in *test* codend.

By using computer-based resampling techniques we were able to simulate the population of catch rate curves p(l) for each experiment. Following the resampling scheme proposed by Millar (1993) we produce a total of B=1000 curves accounting for the between-within haul variation. The confidence intervals have been built up from the simulated population of p(l) curves:

$$\left(p(l)^{\frac{\propto}{2}}, p(l)^{1-\frac{\propto}{2}}\right)$$

Being $p(l)^q$ the quantile of q-order from the estimated population $p(l)^1, \ldots, p(l)^B$, in this case α=0.05

Operational conditions were recorded for each haul, *e.g.* depth, speed, area weather etc. All cod were measured in most hauls and subsampling was limited to one haul. Lengths of flounder and plaice were measured in trials with the Innovative grid system, with the New Bacoma codend and the square mesh codend. This was done because improving the selectivity of flatfish was seen as an objective to reduce discards and to avoid the meshes blocked flatfish decreasing the selectivity for cod.

Four sea trials of about one weak each were conducted. Germany and Sweden conducted one sea trial each and Denmark two sea trials. An overview of the sea trials and of their catches is presented in Table 3.9.

Table 3.9: overview on conducted sea trials.

Sea trials	Country	Test codend	Period	No. hauls	Total numbers caught		
					Cod	Flounder	Plaice
1	SWE	T90 120/s8	March-April	12	11482	-	-
2	DEN	Bacoma 120/130	April	21	19673	17794	7810
3	DEN	Square mesh 120	April	21	8623	20109	9900
4	GER	Freswind Bacoma 120/105	March-April	12	3426	4770	3387

T90 120 s8

Codend design

The fishermen questionnaires indicated that the T90 codend is widely used in the Baltic Sea and generally found acceptable by the fishing industry (section 3.1).

The selective properties of the T90 codend are influenced by several factors other than mesh size, particularly the number of meshes in the circumference and the twine material (Wienbeck et al. 2011; Annex 4; section 3.1). Consequently, there are good reasons for seeking to optimise the selective properties of the T90 codend.

A T90 codend made from single twine has a higher and more stable selection factor (L50/mesh size) over the investigated range of twine diameter, the T90 codends made of double twine that is mainly used today (Annex 4). The selectivity will be sharper when increasing the twine diameter (SR/mesh size is lower) compared to what is used today (Annex 4). A sharper selection curve will reduce capture and hence discards of individuals below MLS and at the same time increase the retention of individuals above MLS. The reason is likely that the thicker twine will ensure a more stable and larger mesh opening and because of the larger knot.

Consequently, there is a rationale for testing improved T90 codends that are expected to give a more stable and sharper selectivity. A T90 codend made from 8 mm single thread with meshes turned 90 degrees was tested (T90 120/s8). The twine is different from the 4 mm double twine used by most of the commercial fleet today. The nominal mesh size was 120 mm, which is the minimum allowed mesh size today.

Sea trials

The Swedish trial was carried out in the eastern and the western Baltic Sea (ICES Subdivision 24, 25 and 26) by the Swedish twin trawler \`Veronica of Fiskebäck\` in March and April 2013. The study was focused on cod, whereas flounder and plaice were only measured as total weight of bycatch.

Table 3.9: Total catches in numbers for cod, flounder and plaice reference codend with the T90 120/s8 codend. Catches are divided by MLS. For flounder the MLS is 21 cm in ICES area 26-28 (Eastern Baltic) and 23 cm that is the MLS in ICES area 22-25 (Western Baltic).

	Reference	New T90	Difference
Cod			
< 38 cm (no.)	1644	1830	11.3%
≥ 38 cm (no.)	3722	4285	15.1%
Total (no.)	5366	6115	14.0%
Ratio < MLS (%)	30.6%	29.9%	-2.3%

Results

Catches of cod are presented in Table 3.9. The new T90 codend caught 11.3% more cod below MLS and 15% more above MLS. Length frequencies and relative catch proportions (proportion of the total catch caught in the test codend) compared to the reference Bacoma codend is illustrated in Figure 3.7. The 95% confidence limits indicates that the catches in the T90 codend are statistical significantly higher in the range from 34 to 44 cm.

Cod

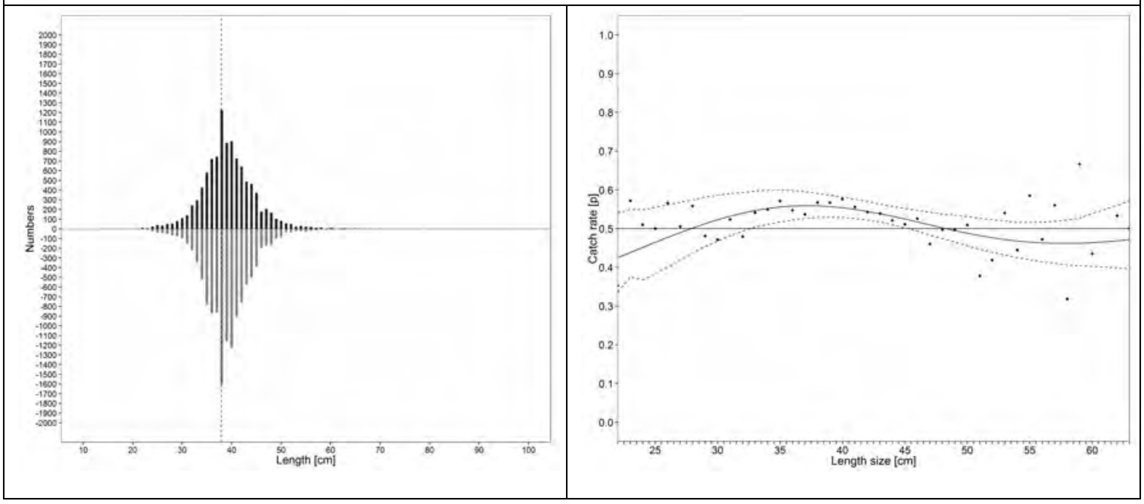


Figure 3.7: Comparing the test codend (T90 120/s8) with the reference Bacoma. Length frequencies on the left, where negative numbers indicate the test codend and positive values the reference codend. On the right relative catch proportions in the test-codend (T90 s8), where values above 0.5 indicate that more fish was caught in the test codend. Dots represent observed proportions for each length class whereas the line indicates the modelled values (solid line mean value and stippled lines 95% bootstrap confidence intervals).

Bacoma 120/130

Codend design

The fishermen questionnaires indicate that the Bacoma codend is widely used in the Baltic Sea. Improvements of this codend would provide a codend that is expected to be acceptable for the fishing industry.

It is documented that cod can escape upwards (upper panel) as well as downwards (lower panel) in the codend (section 3.1). In the presently used Bacoma codend, the upper and lower net panels are made of different nettings having different selectivity properties. The L50 of the 105 mm standard netting used in the lower panel of the Bacoma codend is estimated to 28.6 cm (Table 3.1). This is much lower than the estimate for the knotless square mesh netting used in the upper panel of the Bacoma codend, which is estimated L50 to 46.3 cm (Table 3.1). This discrepancy in the selective properties of the presently used Bacoma codend will have negative consequences on selectivity particularly:

- lower selectivity if cod attempts to escape downwards,
- increased selection range, because of dual selection,
- more escape attempts needed which might cause late escape during the haul-back operation (section 3.1) that will likely increase escape mortality.

Square meshes fit the morphology of cod very well, but do not fit the morphology of flatfish very well (section 3.1). There is a considerable bycatch and discard of flounder in some periods of the year. The selectivity of flounder could be improved, if diamond meshes with larger meshes sizes would be used in the Bacoma codend.

To improve the selectivity, a Bacoma codend was designed where the mesh size of the diamond meshes in the lower panel was increased from 105 mm to 130 mm (here named Bacoma 120/130). The selectivity of the 130 mm diamond meshes was expected to be in better accordance with the selectivity of the 120 square meshes in the top panel. Consequently, this codend was expected to ensure improved selectivity in the lower panel for cod. At the same time, the selectivity was also expected to improve for flatfish. The number of meshes in the circumference in the lower panel was decreased from 50 meshes to 42 meshes to ensure the same mesh opening degree.

Sea trials

Sea trials were conducted in April 2013 in the Eastern Baltic Sea in ICES area 25. The 148 kW powered and 14.6 m long side trawler R86 'Lis-Hansa' was used, and it was rigged for twin trawling. The towing time was limited to around 2 hours to allow for: measuring the whole catch since the potential differences could be very small; a large number of hauls reducing the variance caused by between-haul-variation. Furthermore, also to have similar conditions with the sea trials with the full square mesh codend in the following experiment where it was important not to have high catches because the codend is faster filled up, due to its relatively fixed geometrical shape (see Section 3.2).

Subsampling was made for cod in one haul. The whole catch of cod, flounder and plaice was measured in the remaining hauls. Catches of other species were limited.

Results

A total of 21 hauls were conducted. The overall catches and the differences between the reference Bacoma codend and the Bacoma 120/130 are provided in Table 3.11 for cod, flounder and plaice. Length frequencies are provided and relative catch proportions, comparing the reference Bacoma with the Bacoma 120/130, are provided in Figure 3.8. The Bacoma 120/130 caught 55.3% less cod below MLS (38 cm) than the reference Bacoma codend and 18.0% less above MLS. The catch proportion (Figure 3.8) indicates that the catch efficiency is statistically significantly lower (95% confidence limits clear of the zero line) compared to the reference codend up to around 40 cm and higher around 50 to 55 cm.

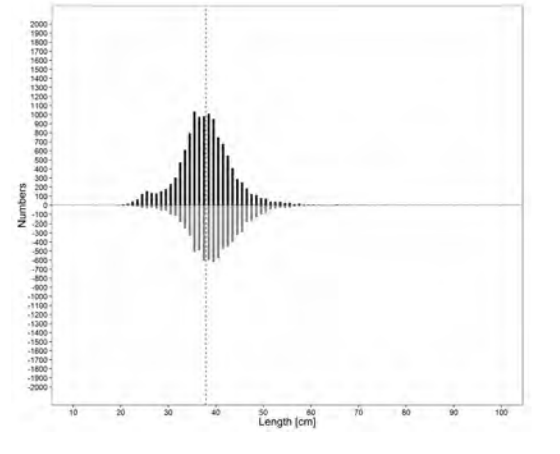
For flounder, the reduction in catches was 46.3% below 21 cm and 40.1% below 23 cm and 13.4% and 11.1% above, respectively. The relative catch proportions indicate that there is a reduced catchability up to around 30 cm.

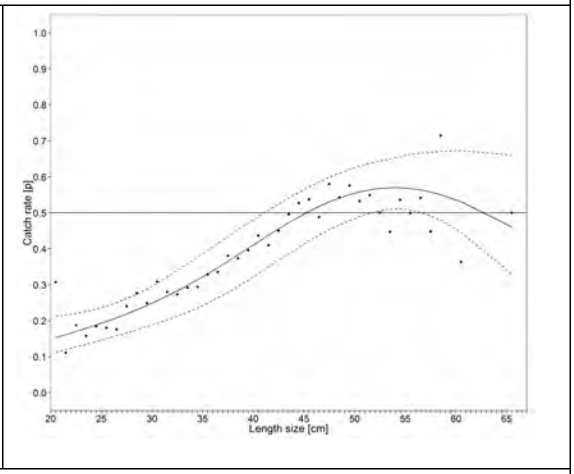
For plaice, the reduction in catches was 53.7% below 25 cm and 27.1% above 25 cm. The relative catch proportions indicate that there is a reduction up to around 30 cm.

Table 3.11. Total catches in numbers for cod, flounder and plaice reference codend with the Bacoma 120/130 codend. Catches are divided by MLS. For flounder the MLS is 21 cm in ICES area 26-28 (Eastern Baltic) and 23 cm that is the MLS in ICES area 22-25 (Western Baltic).

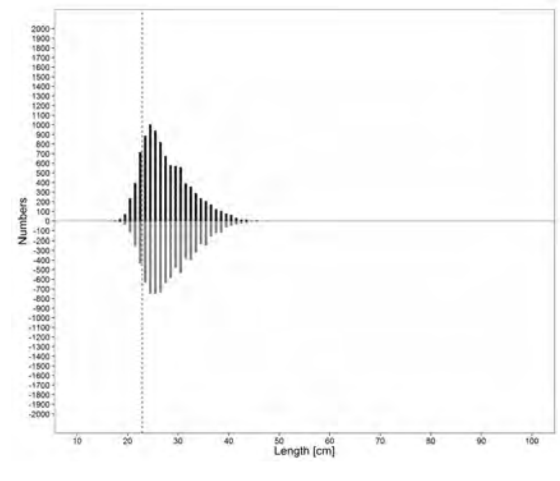
	Reference	Bacoma 120/130	Difference
Cod			
< 38 cm (no.)	6411	2864	-55.3%
≥ 38 cm (no.)	5713	4685	-18.0%
Total (no.)	12125	7549	-37.7%
Ratio < MLS	52.5%	33.4%	-36.4%
Flounder			
< 21 cm (no.)	259	139	-46.3%
≥ 21 cm (no.)	9338	8085	-13.4%
< 23 cm (no.)	1161	696	-40.1%
≥ 23 cm (no.)	8436	7501	-7.9%
Total (no.)	9597	8197	-11.1%
Ratio < 23 cm	12.1%	8.5%	-29.8%
Plaice			
< 25 cm (no.)	1538	712	-53.7%
≥ 25 cm (no.)	3215	2345	-27.1%
Total (no.)	4753	3057	-35.7%
Ratio < MLS (%)	32.4%	23.3%	-28.0%

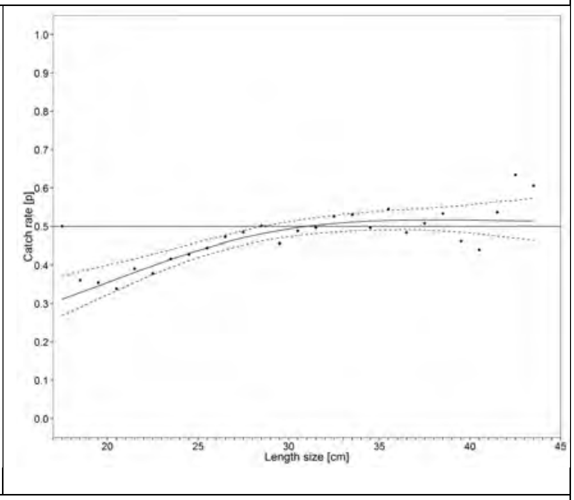
Cod



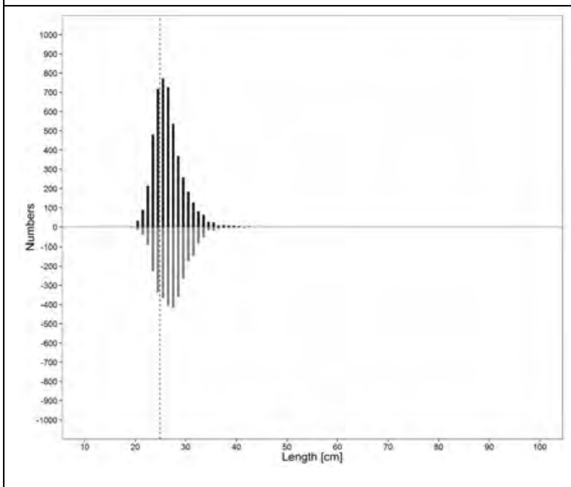


Flounder





Plaice



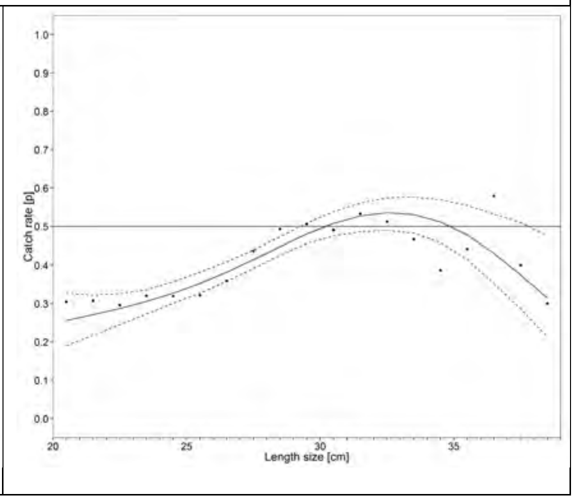


Figure 3.8. Comparing the test codend (Bacoma 120/130) with the reference Bacoma. Length frequencies on the left, where negative numbers indicate the test codend and positive values the reference codend. On the right relative catch proportions in the test-codend (Bacoma 120/130), where values above 0.5 indicate that more fish was caught in the test codend. Dots represent observed proportions for each length class whereas the line indicates the modelled values (solid line mean value and stippled lines 95% bootstrap confidence intervals).

Square 120

Codend design

Square meshes fit the morphology of cod very well (see section 3.1). To improve the selectivity of cod a full square mesh design was constructed having 120 mm square meshes inserted in the top panel, as well as in the lower panel of the codend. This is expected to increase the L50 of the lower 105mm diamond mesh net-panel, which is typically used in Bacoma codends by more than 15 cm for cod (from just below 30 cm to more than 45 cm) and hence providing improved selectivity for cod escaping in a downward direction.

Sea trials

Sea trials were conducted in April 2013 in the Eastern Baltic Sea (ICES area 25). More details on the sea trials are provided in the Bacoma 120/130 section. The whole catch of cod, flounder and plaice was length measured in all hauls.

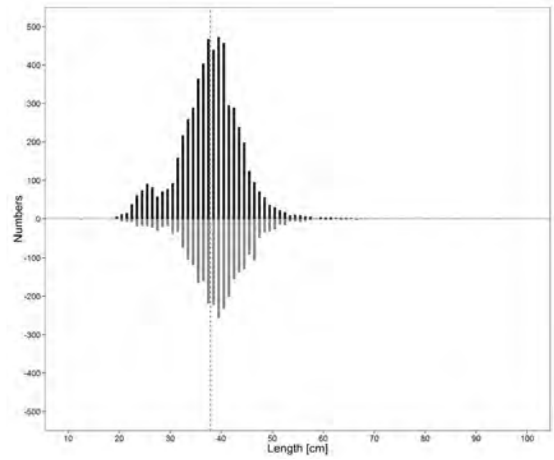
Results

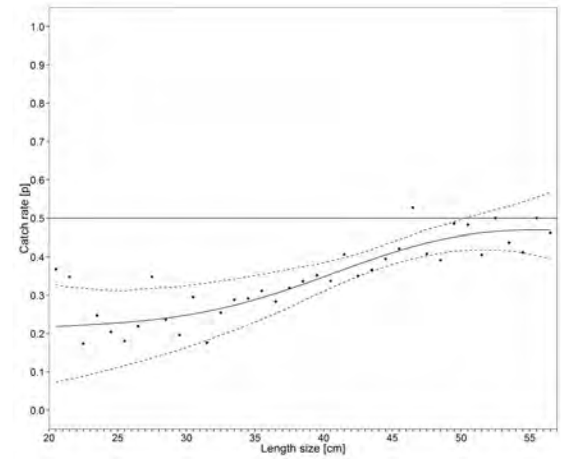
A total of 21 hauls were conducted. The overall catches and the differences between the reference Bacoma codend and the square mesh codend are provided in Table 3.12 for cod, flounder and plaice. Length frequencies are provided and relative selectivity comparing the reference Bacoma with the square 120 codend is provided in Figure 3.9. The square mesh codend caught 61.4% less cod below MLS (38 cm) than the reference Bacoma codend and 39.0% less above MLS. The catch proportion curve (Figure 3.9) indicates that the catch efficiency is statistically significantly lower up to around 50 cm, compared to the reference codend.

Table 3.12. Total catches in numbers for cod, flounder and plaice comparing the reference codend with the Square 120 codend. Catches are divided by MLS. For flounder the MLS is 21 cm in ICES SDs 26-28 (Eastern Baltic) and 23 cm in ICES SDs 22-25 (Western Baltic).

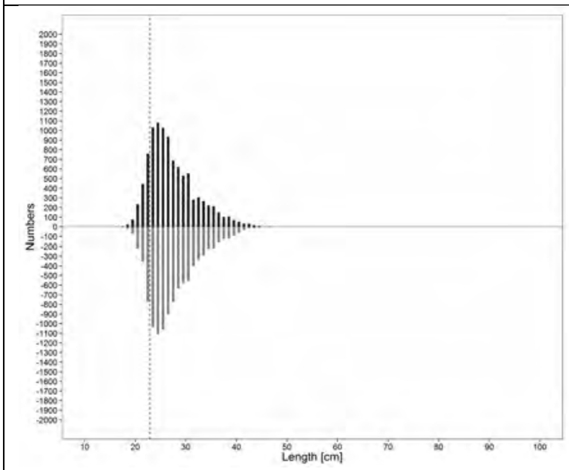
	Reference	Square 120	Difference
Cod			
< 38 cm (no.)	2840	1095	-61.4%
≥ 38 cm (no.)	2911	1777	-39.0%
Total (no.)	5751	2872	-50.1%
Ratio < MLS	49.4%	38.1%	-22.8%
Flounder			
< 21 cm (no.)	341	320	-6.2%
≥ 21 cm (no.)	9536	9912	3.9%
< 23 cm (no.)	1545	1452	-6.0%
≥ 23 cm (no.)	8332	8780	5.4%
Total (no.)	9877	10232	3.6%
Ratio < 23 cm	15.6%	14.2%	-9.28
Plaice			
< 25 cm (no.)	1641	1650	-0.5%
≥ 25 cm (no.)	3305	3304	0.0%
Total (no.)	4946	4954	-0.2%
Ratio < MLS	33.2%	33.3%	0.4%

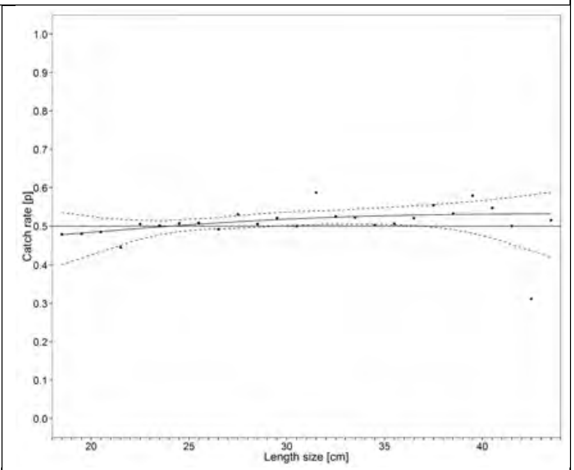
Cod



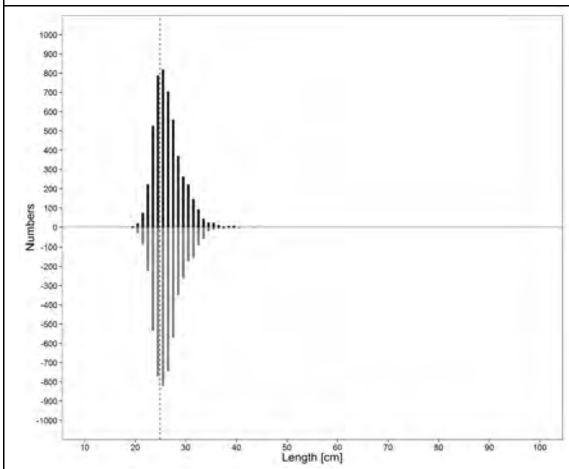


Flounder





Plaice



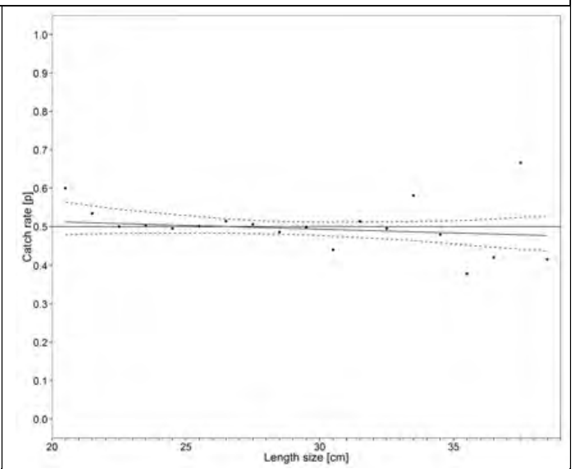


Figure 3.9. Comparing the test codend (square 120) with the reference Bacoma. Length frequencies on the left, where negative numbers indicate the test codend and positive values the reference codend. On the right relative catch proportions in the test-codend (Square 120), where values above 0.5 indicate that more fish was caught in the test codend. Dots represent observed proportions for each length class whereas the line indicates the modelled values (solid line mean value and stippled lines 95% bootstrap confidence intervals).

For flounder, the reduction in catches was 6.2% below 21 cm and 6.0% below 23 cm and 3.9% and 5.4% increase above respectively. The relative catch proportions (Figure 3.9) indicates that the difference is significantly different around 30-35 cm.

For plaice, the reduction in catches was 0.5% below 25 cm and no difference (0%) above 25 cm. The relative catch proportions (Figure 3.9) indicates that there is no significant difference between the test-codend (Square 120) and the reference codend (Bacoma 120/130).

Freswind Bacoma 120/105

Design

This device was designed and various improvements made during trials, with the aim of reducing flatfish catches in the otter trawl cod fisheries operating in the Baltic Sea. This is expected to reduce the unwanted bycatch of flatfish species, as well as to increase cod selectivity by avoiding blocking of the meshes. This device increases the options available to fishers concerning which gear configuration they could use under the future discard ban.

Sorting grids have been successfully used in many years in the Barent Sea cod fishery to reduce undersized cod catches. They have the advantage that they have a high degree of active physical sorting because the cod will encounter the grid when entering the codend, whereas traditional mesh selection depends on an escape reaction from the cod. This will reduce the amount of cod that escapes late on the capture process during haul-back with an expected higher mortality rate (section 3.1).

One of the characteristics of the grids in use is the vertical orientation of the bars, and therefore the bar spacing. This orientation matches the natural swimming orientation and the bilateral symmetry of round fish, improving the escapement likelihood of roundfish juveniles when contacting the grid. In contrast, for a flatfish to escape through the grids it would need to turn to slide through the vertical bar orientation.

The VG device (Vilnis Grid device, Figure 3.10) was originally designed by the Swedish Fisher Vilnis Ulups (Karlskrona, SF345) to reduce the by-catch of flatfish species in Baltic cod trawl fisheries. The original design consisted of 4 stainless steel grid windows 600x500mm, with a bar spacing of 45mm, fitted to the sides of the end of the belly section. The novelty of this design is the horizontal bar orientation, matching the flatfish body orientation in their natural swimming behaviour. The bars are oriented in parallel to the towing direction, in a way that the alternate bars represents fissures in the belly matching with the transversal shape of flatfishes, while only smallest roundfish individuals are expected to have any chance to escape. In summary, the VG device can be seen as a mixed selection device, but primarily designed to improve the size selection for flatfish species.

Figure 3.10. Hauling of the trawl with the first design of the grids device and the video recorder setup (white float).

This first design of the VG, proposed by the Swedish fishermen, was tested onboard the German research vessel Clupea. The first sea trials were performed at about 15m depth off the German coast. Two hauls were conducted using the first version of the device, which included two pairs of grids attached to the sides of the belly section (Figure 3.10). The device was mounted in one of the trawls in a standard twin trawl setup with standard BACOMA codends (120mm/105mm). A video recorder (GoPro HERO2 HD, 1080p/30fps) was mounted in the roof of the trawl about 0.5 m in front of the grid system. After each hauls, the video recording was retrieved and the total catch was analysed to species, length and total weight.

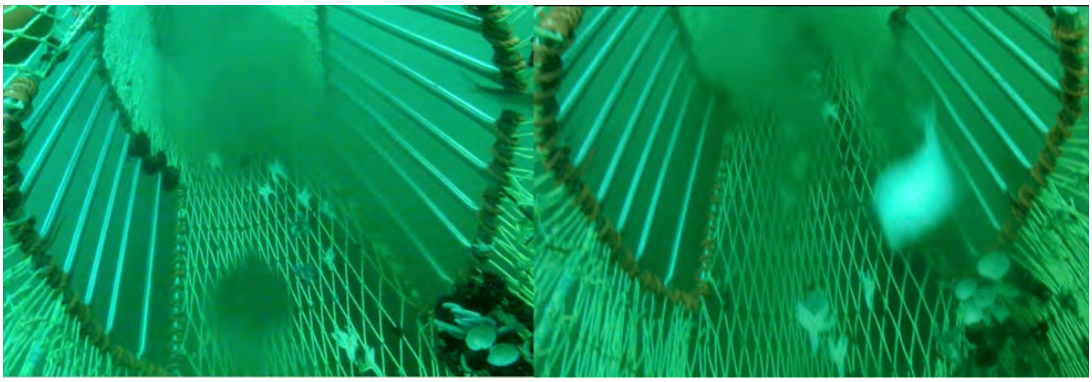


Figure 3.11. Left: An image from the first haul when all 4 grid windows were observed in the image. A flatfish is visible swimming on the floor of the trawl in the trawling direction passing the observed area very quickly. A cloud of resuspended sediment is covering the second pair of grid windows. (b) Right: An image from the second haul. A flatfish showing the “blind side” just before escaping the trawl through the grid window to the right in the image.

No differences in the catch between the two gears (with and without the first version of the grid) were observed. Additionally, it was seen from the underwater video recordings that most flatfish passing the area, where the grids are mounted, do not get in contact with the grid and, therefore cannot make use of them.

Nevertheless, it was decided by the research team to follow up this potential gear modification and to improve the design in a way to improve the efficiency of the grid.

The design of the VG-device was successively improved thanks to the data obtained in two additional research cruises, carried out by the German RV 'CLUPEA'. During these additional cruises, three different versions of the grid were developed, until the last version 'Freswind' Bacoma 120/105, which was then used (together with a Bacoma 120/105 codend) in the catch comparison experiment against the standard gear (Bacoma 120/105).

Sea trials of final grid system

The sea trials were carried out by the fishing vessel 'CRAMPAS' (SAS 107), a 17.4 m length, 219 kW German twin trawler. The bad weather conditions and some technical problems not related to the selective device caused that only 13 hauls were successfully sampled between 14.03-26.03.2013. The fishing area was decided by the skipper under the restriction that catches should present sufficient amounts of both roundfish and flatfish, to allow precise inferences during the data analysis. The fish species used as reference for comparison were cod, flounder and plaice. Length size and biomass information were measured with no sub-sampling for cod, flounder and plaice, whereas only weight was recorded for other species.

Results

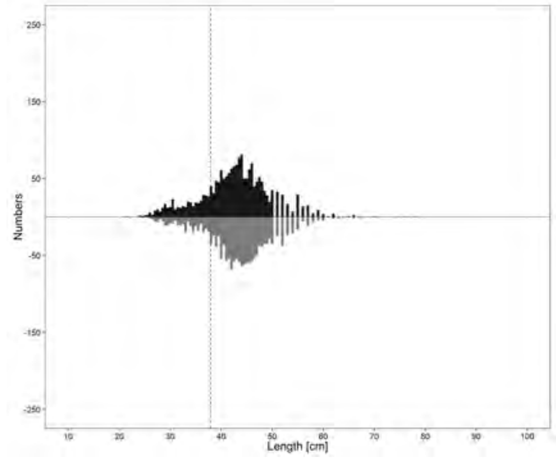
Table 3.13 shows the absolute catches from the 13 valid hauls conducted, and the catches divided by MLS.

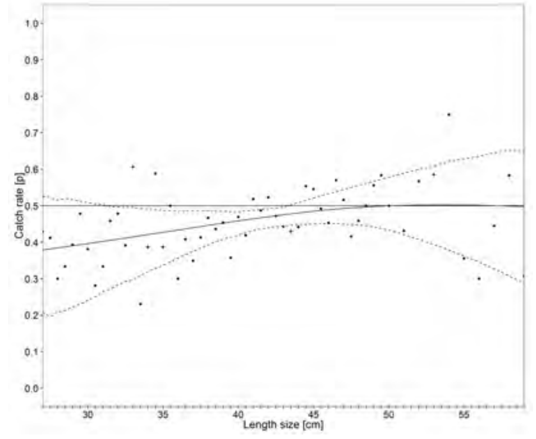
The cod catch in the test trawl was mainly composed of marketable individuals but the undersized catches were sufficient to assess the potential effect of the Freswind grid on these length classes. In general, cod catches were slightly lower than those obtained by the reference Bacoma codend (~12% reduction). Nevertheless, this difference is mainly found for the undersized fraction (~32% reduction)

The catches of flatfish species were higher than cod catches, showing that the skipper was successful in choosing the right fishing ground to carry out this experiment. Flounder catches were significantly lower in the test trawl. The overall reduction was ~60%. Surprisingly, the difference between trawls was higher for the undersized fraction (~10% higher reduction for undersized fraction than for marketable).

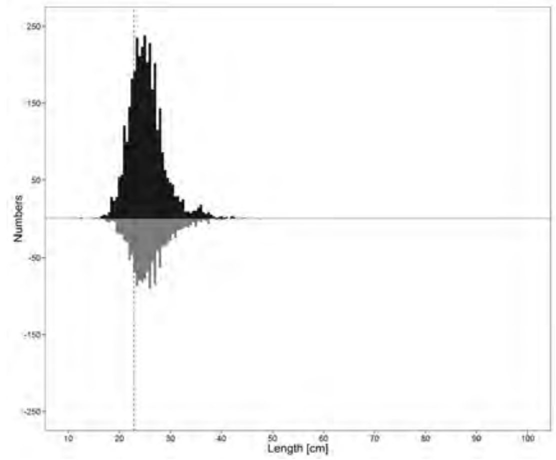
Plaice showed a similar trend to the flounder catch comparison, although the global reduction was slightly lower compared to the flounder results (~56% vs ~61%). Again, the results indicate an interaction between the degree of catch reduction and the catch fraction. The difference between both undersized and marketable fraction was again ~10%.

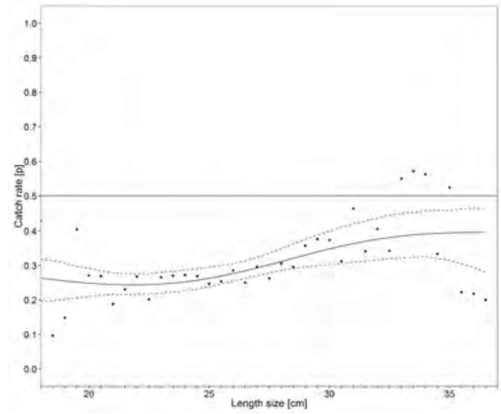
Cod



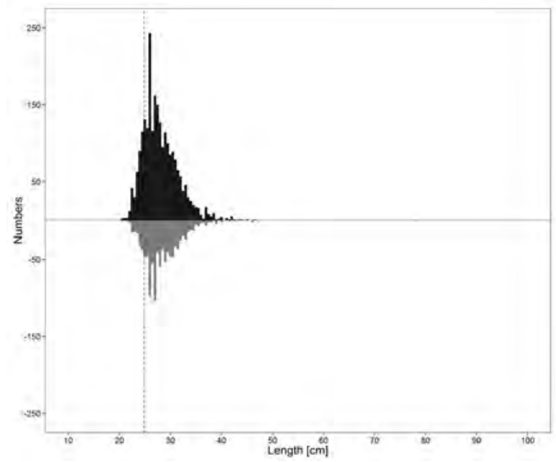


Flounder





Plaice



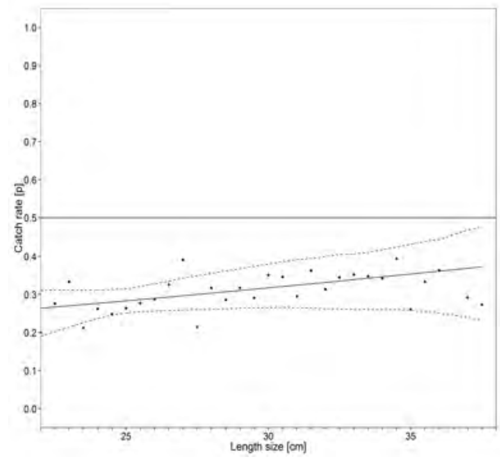


Figure 3.12. Comparing the test codend (Freshwind Bacoma 120/105) with the reference Bacoma. Length frequencies on the left, where negative numbers indicate the test codend and positive values the reference codend. On the right relative catch proportions, where values above 0.5 indicate that more fish was caught in the test codend. Dots observed proportions for each length class whereas the line indicates the modelled values (solid line mean value and stippled lines 95% bootstrap confidence intervals).

The relative catch proportions of cod (Figure 3.12) shows a positive slope meaning that on average, the test trawl catches less small individuals than the reference trawl. Nevertheless the Confidence Intervals of the curve estimation indicate that there is no a significant difference between trawls in most of the length range, except for the length range around the MLS.

Flounder and Plaice models show a similar functional form. Both mean curves are below the equality line (p=0.5), meaning lower flatfish catch expectations for the test codend in all length size range. Nevertheless, there is an increasing trend from the smallest to the largest individuals in both cases. This tendency is more pronounced in the case of the Flounder curve, showing a smooth S-shape compared with the linear shape of the Plaice curve. The CI did not reach the equality line (p=0.5) in both cases meaning that there is a significant difference over the length range for both species.

Table 3.13. Total catches in numbers for cod, flounder and plaice reference codend with the Freswind Bacoma 120/105. Catches are divided by MLS. For flounder the MLS used was 23 cm that is the MLS in the ICES area 22-25 (Western Baltic), the area the trials were carried out.

	Reference codend	**Freswind Bacoma 120/105**	Difference
Cod			
< 38 cm (no.)	377	255	-32.4%
≥ 38 cm (no.)	1447	1347	-6.9%
Total (no.)	1824	1602	-12.2%
Ratio < MLS (%)	20.7%	15.9%	-22.9%
Flounder			
< 23 cm (no.)	760	237	-68.8%
≥ 23 cm (no.)	2677	1096	-59.1%
Total (no.)	3437	1333	-61.2%
Ratio < MLS (%)	22.1%	17.8%	-19.6%
Plaice			
< 25 cm (no.)	360	124	-65.6%
≥ 25 cm (no.)	1994	909	-54.4%
Total (no.)	2354	1033	-56.1%
Ratio < MLS (%)	15.3%	12.0%	-21.5%

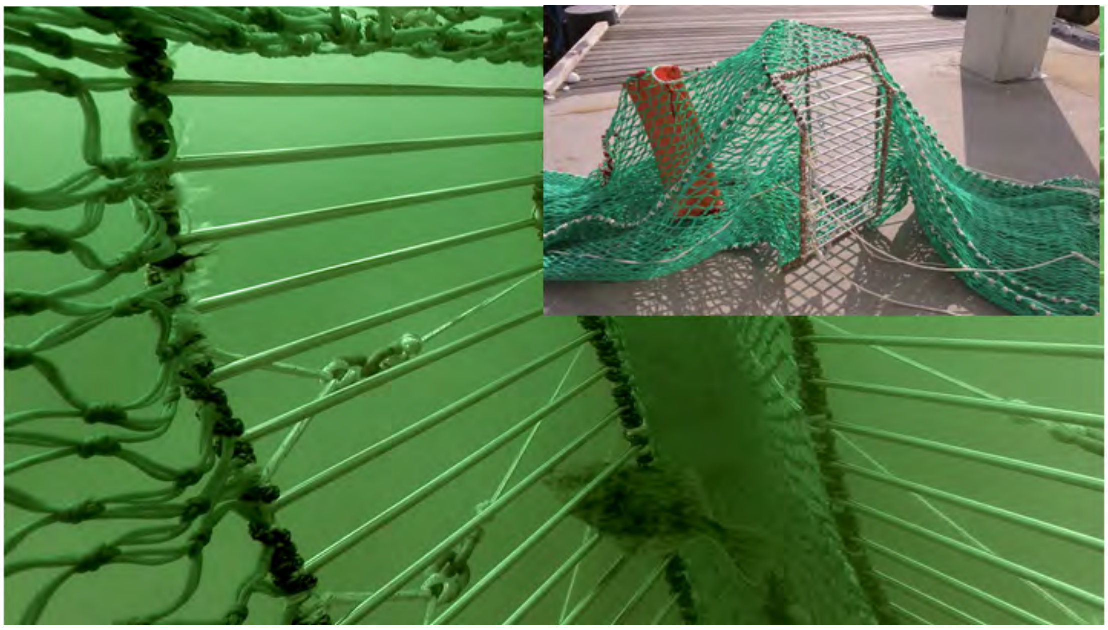


Figure 3.13. Underwater recording of the Freswind during towing and a flounder escaping through the grid (canvas obstacle not shown here). Harbour picture showing the canvas obstacle (top-right).

Discussion and conclusion

The fishermen questionnaire indicates that both, the Bacoma and T90 codends are widely used by the fishermen. There are several critical comments to both codends, but they are not going in the same direction. This suggests that the experience is very dependent on the individual fisher and the conditions he is experiencing during fishery. Consequently, we have tested four rather different concepts during the commercial sea trials.

T90 s8

Compared to the reference Bacoma codend, the T90 120 s8 codend release less cod just around MLS, but the difference is not that marked compared to the other gears tested.

Bacoma 120/130

The Bacoma 120/130 had a high reduction of cod below 45 cm, but also higher catches above 45 cm. The difference was, however, only found statistical significant in a limited length span. The lower catch weight in the more selective Bacoma 120/130 might cause differences of the water flow or drag of the trawl that could make a limited change on catch rates of the larger cod. In numbers, there is a loss in catches above MLS because there is a high proportion of the cod just above MLS. In weight, the loss will be less because of the increased catch of larger cod. The increase in diamond mesh net size gives a marked reduction in catches of flounder and plaice below 30 cm. Increasing the mesh size of the diamond netting from 105 to 130 mm in the lower panel of the Bacoma codend used today is a very simple and cheap way to improve the selectivity. The selectivity of all species can be adjusted by the diamond net mesh size in the lower panel. Fishers will often have higher catches than experienced in these sea trials. However, previous experiments did not indicate any catch size effect using a Bacoma window (Madsen et al., 2002; Madsen et al., 2010). Also we did not observe any significant increase of discard rates due to larger catches in the desktop study (Figure 2.7). It is unlikely that the catch will influence the mesh figuration of the square mesh netting in the Bacoma window. But the mesh opening of the diamond mesh netting will be influenced by catch weight (Hermann, 2005) and the accumulating catch will move up in the region where meshes are more closed compared to the area around the lifting strop (section 3.2). The more closed meshes in this region are likely to reduce selectivity of cod but increase it for flounder and plaice (section 3.1).

Square 120

The reduction of cod below and above MLS is in the Square 120 codend is higher than observed for the Bacoma 120/130. This was also to be expected since the selectivity of a 120 mm square mesh is higher for cod than it is for a 130 mm diamond mesh. At the same time the selectivity of flounder and plaice is only slightly different compared to the reference Bacoma trawl. With this codend, there will be a significant loss of cod up to about 50 cm and the immediately economical loss of the fishermen would be high. The mesh size would hence have to be lower to decrease this loss. The flumetank test indicated that the Square 120 codend will be filled up faster than the Bacoma and T90 codend and that the codend is likely to be filled up when exceeding catches of 1.5 tonnes. Consequently, it will be necessary to increase the length of the codend if the selectivity should not be affected when experiencing larger catches. The benefit from the catch building up in a forward direction is considerable lower energy consumption, compared to codends where diamond meshes are used. The price of the knotless netting used for square mesh panels is considerable higher than traditional diamond mesh netting. The flumetank test of the Bacoma T0 indicates that it is possible to remove the tension on the netting, which might make it possible to use cheaper net materials that are not expected to perform well under tension.

Freswind Bacoma 120/105

One of the main aims of the Freswind Bacoma 120/105 device was to reduce flatfish catches while keeping cod catchability of cod above MLS. The catch efficiency of cod for length classes smaller than MLS were slightly reduced. One possible explanation is that cod is released through the grid device. Cod fall-through trials, using the same grid as the one fitted to the gear, were carried out on board to assess potential grid size selection on cod. Although these experiments have not been analysed for the time being, it has been observed that length sizes up to 40 cm would be able to physically escape through the grid. Another explanation could be that the reduction in flatfish catches may reduce the number of codend meshes tapered by the flatfish. This scenario may improve the chances of cod to contact the open meshes and therefore being able to escape from the catch.

The results indicate a high flatfish catch reduction (in both cases above 50%), showing the success of the original grid device idea coming from the fishing industry, and subsequently developed and improved under scientific advice. The increasing trend in the catch comparison curve for the flatfish species indicates length dependency on the escapement rates. A likely explanation is behavioural differences between juveniles and adults when approaching the grid. We believe that small individuals are drifted by the flow until they contact to the grid, while larger individuals would be able to elude the contact by actively change the swimming direction. Another potential explanation is that the contact orientation (the angle of attack of the fish body to the horizontal bar spaces) can be more determinant for larger individuals than for smaller.

The grid device was fitted to the trawl belly and fish are expected to come in contact with the grid when they pass through the trawl towards the codend. Consequently, these fish will be released in their natural environment reducing late escape during haul-back (Herrmann et al., 2013), which might increase survival rates for escapees.

The assessment of the economic performance of the tested codends (T90 120/s8, Bacoma 120/130, Square 120, and Freswind Bacoma 120/105) and of the reference codend (Bacoma 120/105 Ref) are presented in the next chapter.

4 Impact study - Impact evaluation of the proposed solutions

A study was carried-out to assess the short-term economic performance under different management scenarios (different codend, different minimum landing size and discard ban) for a standardized vessel. It also undertook a medium-term projection of a stock assessment affected by the selectivity of two different trawl (codend) designs. The designs used for the impact studies are the codends most preferred by the industry (Bacoma 120/105) and the codend with best overall performance relative to economical performance and discard rates in the short-term analysis below (Bacoma 120/130).

4.1 Short-term economical impact of suggested technical measures on different stock size class distributions

The aim of the economic impact study is to evaluate the short -term effects of different technical measures and how these measures may interact with different size class structures of the Baltic cod stock. In the short-term analysis, no stock effects are considered and thus all effects are based on the costs and revenues for fishing a pre-determined quota in one year. The economic performance of a fishery is directly dependent on quota, stock size, size distribution of target species, and technical measures. We have analysed the economic impact of 60 different scenarios built around four main factors.

Factors

The factors defining the scenarios are gear selectivity, MLS, discard ban, and the size distribution of cod in the stock.

Gear selectivity (retention likelihood)

Most of the size selectivity is known to take place in the rearmost part of the trawl (i.e. the codend). During the commercial vessel sea trial we tested 4 codends against a reference codend (Bacoma 120/105, 120 mm Bacoma window and 105 mm diamond mesh in the lower panel). The size selectivity of a gear could be expressed as the retention likelihood. Retention likelihood describes the probability for each size classes to be retained in the codend. We used the catch ratios obtained during the catch comparison experiment to redefine the original reference mean retention likelihood (Figure 4.1).

The trawls used for the gear retention likelihood scenarios were:

- Bacoma 120 mm/105 mm (Ref; Reference codend)
- Freswind (grid system) with a standard Bacoma 120 mm/105 mm codend
- T90 120 mm single 8 mm
- Bacoma 120 mm/130 mm
- Square mesh 120 mm

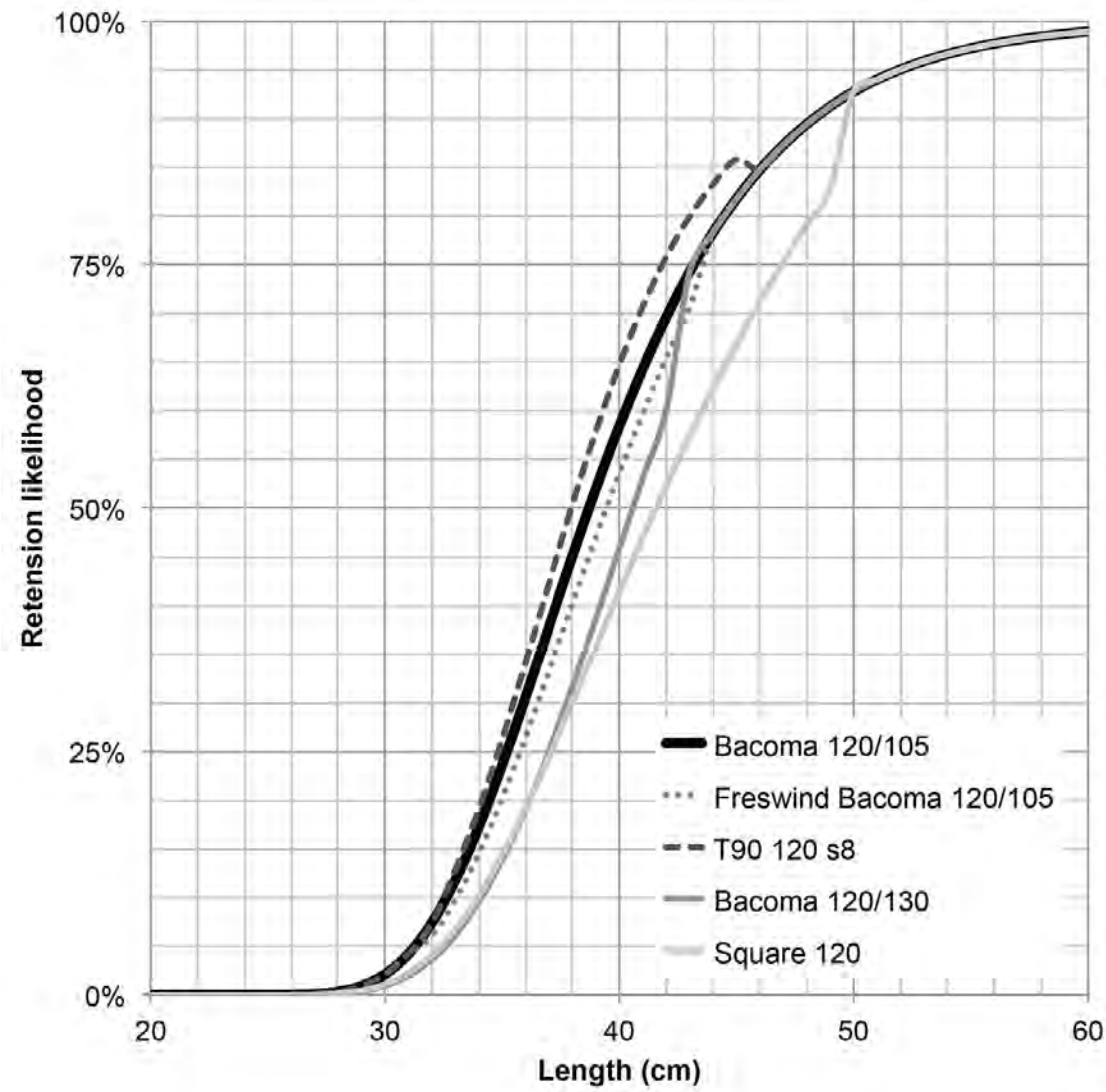


Figure 4.1. Retention likelihood of the reference codend Bacoma 120/105 and the codends tested in the commercial vessel sea trial (for details see Annex 5: Commercial Vessel Sea Trial). The L50 value is the length of cod where half of the individuals (50%) are retained in the trawl and half of the individuals are not.

Minimum landing size (MLS)

In the Baltic cod fishery, the current minimum landing size is 38 cm. MLS was increased in 2003 from 35 cm and before that from 33cm in 1995 (Suuronen et al. 2007).

Minimum landing size scenarios used were:

- 35 cm
- 38 cm

Discard ban

A major change in the new common fishery policy (CFP) is the introduction of a discard ban, which will be introduced into the Baltic Sea cod fishery in 2015 (EC 10629/13 PECHE 245 CODEC 1359). We analysed the economic impact of introducing a discard ban in the Swedish Baltic Sea cod fishery under the assumption that the ban is fully enforceable. In this study we have set the catch quota equal to the landing quota before the discard ban. This results in the same total landing, but divided in marketable catch (>MLS) and not marketable catch (<MLS).

Discard ban scenarios:

- no Discard ban (landing quota)
- Discard ban (catch quota)

Size distribution of cod in the Eastern and Western Baltic Sea

Together with gear selectivity the size class distribution have a direct effect on the relation between landings and discards. Even if the population structure only indirectly could be influenced by management it is of great importance to consider this factor in an analyse of discard rates together with gear selectivity. Data on spatial and temporal distribution of all size classes of cod were collated from the Baltic International Trawl Survey (BITS) database. Averaged length distribution was calculated for the three time periods 1991-2000, 2001-2010 and 2011-2013 (quarter 1) for each ICES subdivision SD24 and SD25 (Figure 4.2).

Size distribution scenarios used were:

- 1991-2000 (1990s)
- 2001-2010 (2000s)
- 2011-2013 (Q1, 2010s)

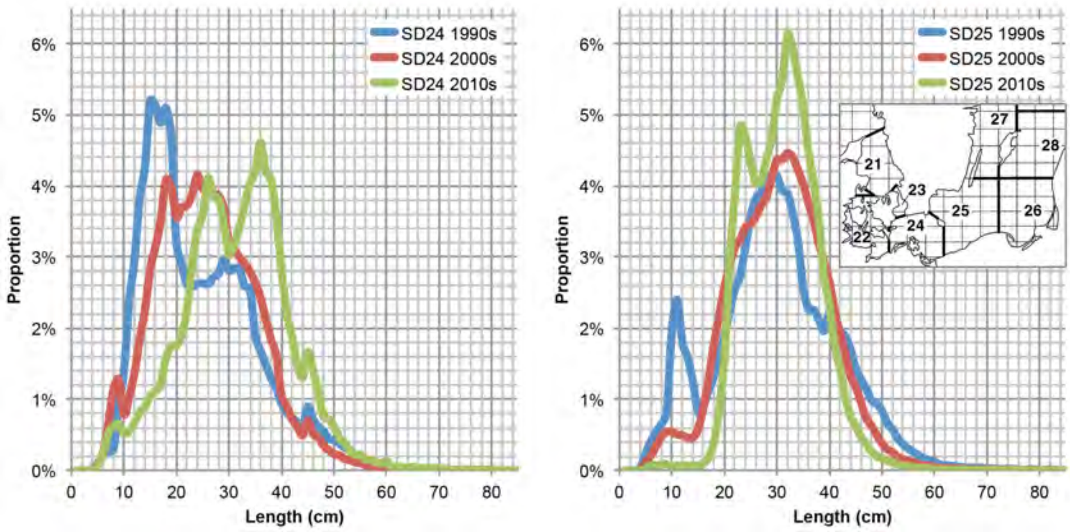


Figure 4.2. Average size distribution of cod in number in ICES subdivision SD24 and SD25 between 1991-2000, 2001-2010 and 2011-2013 collected in Baltic international trawl survey. Map showing ICES subdivision SD21 to SD28 in the south of Baltic.

Economic model

Catch composition

Catch compositions for the different scenarios were calculated by multiplying the relative number of individuals in each size class in the respective stock with the retention likelihood for each size class and gear (Figure 4.3). This procedure generated the number of individuals retained in the trawl and lost (cod not selected by the specific mesh) in each size class in each combination of size distribution and stock. Both the number of retained and lost individuals was then divided into individuals below MLS and into the 5 EU commercial size-categories above MLS (38-48, 49-62, 63-79, 80-95 and >96cm). The total weight of both lost and retained individuals in each of the scenarios gives the total amount of cod (kg) passing through the trawl (PTT) needed to catch a certain amount of fish. A theoretical example is provided below.

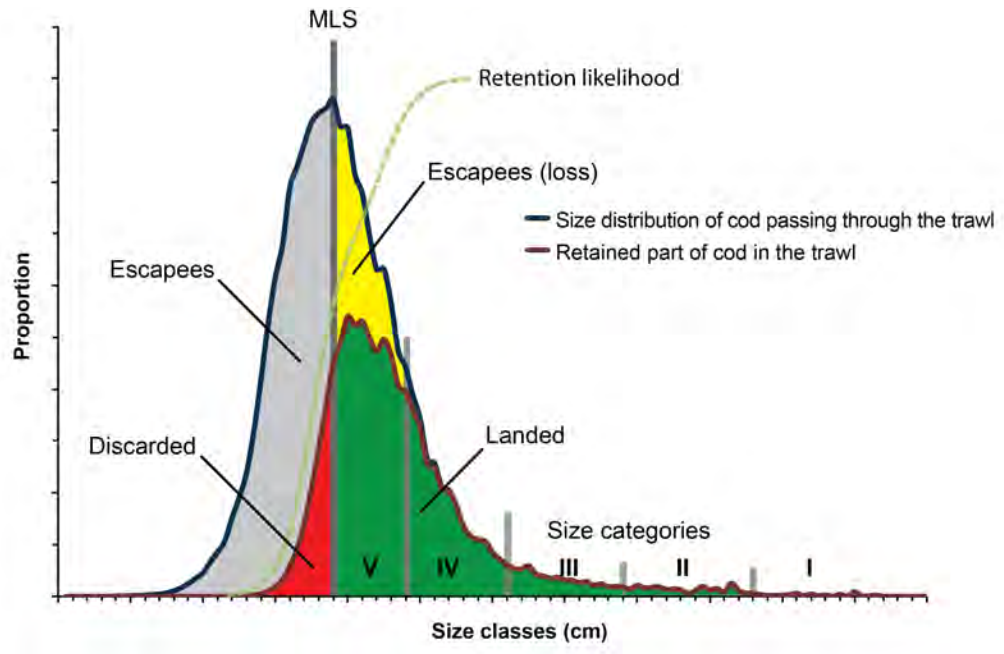


Figure 4.3. Theoretical example of retained and escapees of the total size distribution of cod depending on gear retention likelihood. The grey area represents the amount of fish passing through the trawl that is not retained and that is below MLS. The red area represents the amount of fish that will be caught and discarded. The yellow area represents the amount of fish above MLS, which is not retained. The green area is the catch above MLS, which is divided in the 5 EU commercial size categories (I to V, where V is the smallest size category). The amount of fish in the red area will be landed in a scenario with a discard ban and discounted the quota but not giving any revenue.

Revenues and Costs

The Swedish cod quota is allocated to individual fishermen on a yearly basis, and the management could be described as an individual non-transferable quota system. The yearly quota allocations used in the model was for vessels less than 161 BT corresponding to the size category used for cost calculations. The quota was split between SD24 and SD25, where the latter is the most important area in terms of catch possibilities for the Swedish fishery. The two stocks have different fish abundance and size distributions, which implies that the catch rate per hour and the amount of fish passing the trawl per hour differs.

The economic analysis was based on a model calculating the revenues and costs for a vessel fishing its yearly quota in each of the different scenarios. Revenues were calculated as the landings times the price for each of the size categories. Total cost was the days at sea necessary to catch the quota (*DAS*) times the cost of operating a vessel one day (C_{DAS}). The time necessary for catching the quota will differ between scenarios since the trawling efficiency will differ depending on gear design and stock composition.

The total landings, including undersized fish in the case of a discard ban, will always equal the quota. It was assumed in the model that the quota is always caught, which is a realistic assumption as long as the fishery is profitable.

Economic data

Landed volume for each size category of fish was calculated as the share of fish in the relevant scenario multiplied with total quota (Table 4.1). The price for each size-class is calculated from landing declarations in 2010 for Swedish landings of cod in Baltic Sea harbours. The operating costs were based on economic data from EU's Data Collection Framework (DCF). The costs were defined as fuel costs, repair costs, other variable costs, and fixed costs that are not due to capital investments (e.g. harbour fees). All costs were based on trawlers between 18 and 24 meters primarily fishing for cod in the Baltic Sea in this analysis. This vessel size segment is the dominant fleet category (43% of all Swedish landings of cod in the Baltic) in the Swedish cod fishery in the Baltic. This fleet segment is also one of the dominant within the total cod fishery in the Baltic Sea (25% of the total landings in the Baltic Sea; Table 1.1). The difference between landing value and operating costs is the gross value added (GVA) and does not take fixed costs into account since the vessels are assumed to be identical. The GVA shall cover capital costs, labour costs and profit for the industry.

Table 4.1. Data for calculation of economic performance. Price refers to the EU commercial size category.

Data input	SD24	SD25
Price, small (€/kg), EU size 5, 2010	1,23	1,23
Price, medium (€/kg), EU size 4, 2010	1,56	1,56
Price, large (€/kg), EU size 1-3, 2010	1,71	1,71
Cost per DAS (€)	2 121	2 121
Catch rate per hour (kg), mean 2000-2012	236	306
Pass through trawl per day (kg), PTT_{DAS}	7 640	12 387
Vessel quota (kg)	47 520	376 200

Economic performance (short-term)

On average the largest effect on economic outcome of a single factor was obtained by the stock size class distribution (on average 71 % greater outcome for 1990s distribution compared to 2010s), followed by gear selectivity (on average 11 % greater outcome with the T90 codend compared to Full square codend), changed MLS (on average 11 % greater outcome with MLS 35 cm compared to 38 cm) and finally the discard ban (on average 8 % higher outcome with no discard ban). Table 4.2 shows the economic performance in all scenarios in relative values in relation to the present situation using a Bacoma (120/105) standard codend (scenario: no discard ban, MLS of 38 cm and 2010s size distribution).

Table 4.2. Relative economical performance compared to the today situation with no discard ban, MLS=38 cm and Bacoma 120/105 (Ref), in the Swedish Baltic cod trawl fishery.

Size distribution	Discard ban	No		Yes	
	Gear/MLS	35 cm	38 cm	35 cm	38 cm
1990s	Bacoma 120/105 (Ref)	1.68	1.66	1.64	1.54
	Bacoma 120/130	1.66	1.65	1.64	1.57
	Square 120	1.63	1.62	1.61	1.54
	Freswind Bacoma 120/105	1.67	1.66	1.63	1.55
	T90 120 s8	1.69	1.67	1.64	1.54
2000s	Bacoma 120/105 (Ref)	1.43	1.36	1.37	1.17
	Bacoma 120/130	1.37	1.32	1.33	1.19
	Square 120	1.31	1.25	1.27	1.12
	Freswind Bacoma 120/105	1.41	1.35	1.35	1.17
	T90 120 s8	1.46	1.39	1.39	1.18
2010s	Bacoma 120/105 (Ref)	1.17	**1**	1.09	0.77
	Bacoma 120/130	1.03	0.89	0.99	0.74
	Square 120	0.94	0.76	0.89	0.62
	Freswind Bacoma 120/105	1.12	0.96	1.05	0.75
	T90 120 s8	1.23	1.06	1.14	0.80

Figure 4.4 shows the interaction between a discard ban and MLS as an average over all stock size class distributions (1990s, 2000s, 2010s) and gear designs (codends). The economic performance is dependent on both the MLS and of a discard ban, where the discard ban decreases vessel performance and a lower MLS (35 cm) increases performance. Reducing MLS to 35 cm will increase the economic performance enough to eradicate the negative effect of a discard ban on vessels economic performance (Figure 4.4). The result holds if assuming average prices for the studied period instead of 2010 prices, but not if the price of small cod is reduced by 5 % (e.g. due to increased supply of small cod and lower average weight due to reduced MLS). Further, from table 4.2 it is clear that compensating a discard ban with lower MLS is more efficient in size distributions with a higher share of small fish (2000s and 2010s). Almost two-thirds of the answers in the fishermen questionnaire pointed out MLS as an important or some important management tool to diminish discard rates.

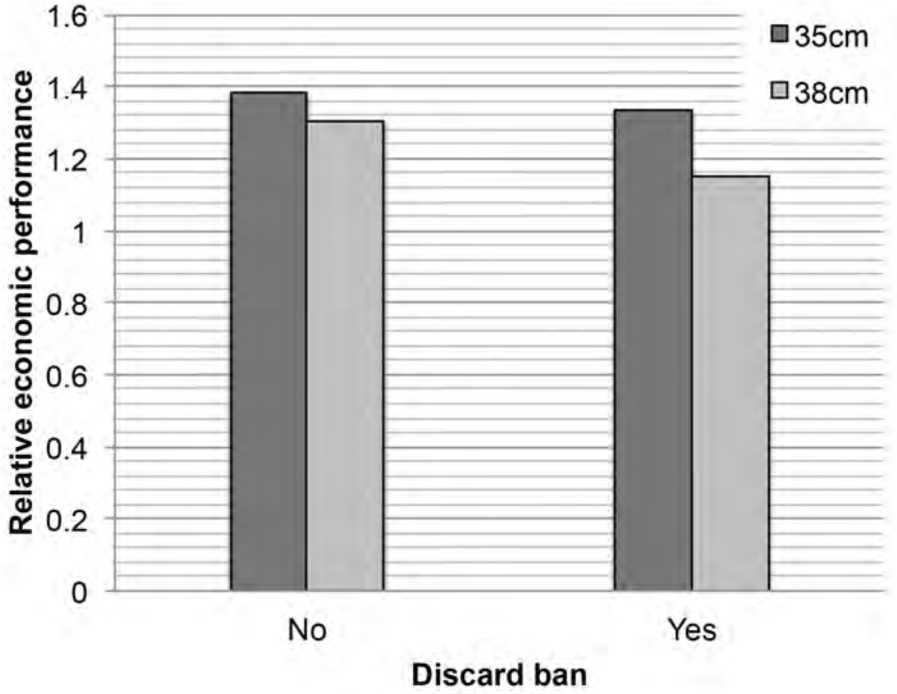


Figure 4.4. The effect of a discard ban and different MLS on the economic performance of a standard vessel.

The effect of size class distribution (per time period) and gear selectivity on the economic performance, suggests that the effect of gear selectivity on economic performance is dependent of the size structure on the stock (Figure 4.5). In the 1990s, the effect of the different gear selectivity on the economic performance, have only a minor effect with a maximum of 2 % of the outcome between the most selective gear (Full square 120) and the less selective gear (T90 120), and even less if we take into account a discard ban (Table 4.2). On the other hand, taking into account the latest size class distribution (2010s), the economic performance varies up to 31 % between different gear types. This means that the effect, in terms of short-term economic loss of an introduction of more selective gear, is more pronounced at present situation when smaller size classes dominate the size distribution.

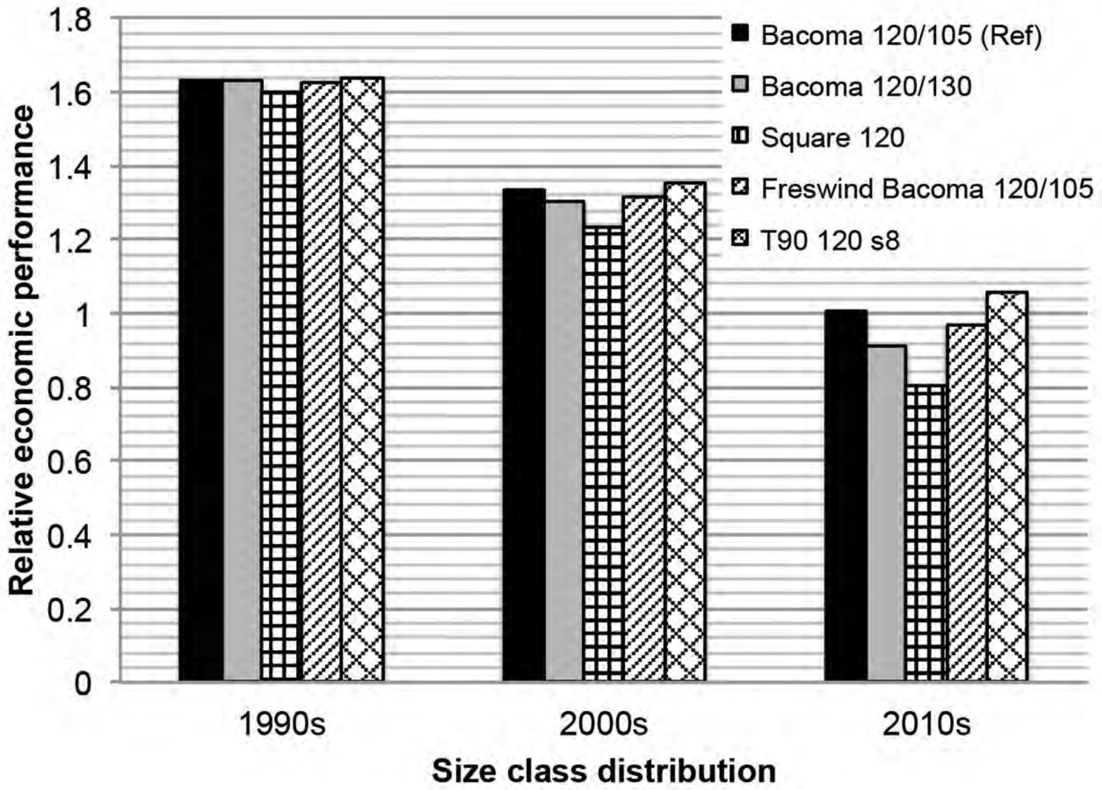


Figure 4.5. The interaction between size class distribution and gear selectivity on vessel economic performance as an average over all MLS and discard options.

The larger effects in the 2010s size distribution implies that the effect, in terms of short-term economic losses, of an introduction of more selective gear is more pronounced when the size distribution is dominated by smaller size classes. This is explained by the relatively high loss of individuals just above 38 cm in the 2010s scenario due to an overall smaller size structure in 2010s compared to 1990s. A sensitivity analysis shows that the differences between gear with high and low selectivity is reduced when the fish is abundant and the size distribution contains a higher share of large fish.

4.2 Medium-term forecast as a result of increased selectivity

The medium-term forecast focus on biological consequences of gear selectivity taking the dynamic effects of selectivity on the stock development into account. We used the input and output data from the latest assessment (WGBFAS 2013) to run a forward stock projection with the status quo selection, i.e. Bacoma 120/105 (Ref), and then we compare it to a similar forward projection but assuming a selection curve (retention likelihood) based on the Bacom120/130 codend.

The shift from a Bacoma 120/105 (Ref) to a Bacoma 120/130 codend will in theory only affect cod sizes between 30 and 42 cm. This shift in selection pattern was used to calculate the theoretical retained length classes of cod with the Bacoma 120/130 codend. Successively, we applied this selection on the length frequency distributions of cod caught by the Swedish cod trawl fisheries in 2013 (Data collection framework, DCF, 2013).

The forecast was based on the FLR routine and it simulated the stock and the catches forward in time starting from the estimates obtained at the 2013 stock assessment meeting (WGBFAS 2013).

Medium term

The medium-term forecast suggests that the Bacoma 120/130 codend would result in a slightly higher (approx. 1 % 2017) SSB irrespectively of recruitment type assumed (Figure 4.6).

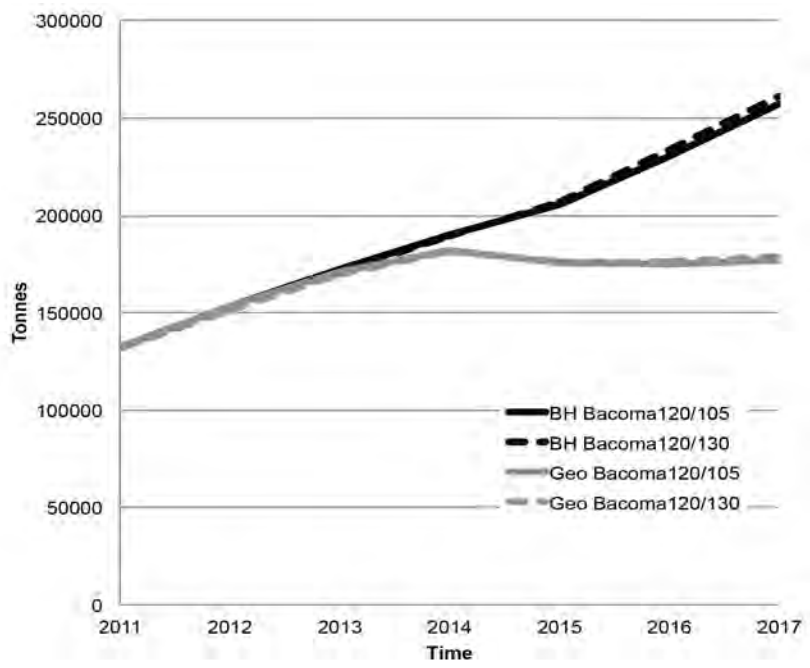


Figure 4.6. The development of the spawning biomass for the Bacoma 120/105 (Ref) codend and the Bacoma 120/130 codend using geometric mean recruitment (Geo) and recruitment as estimated by fitting a Beverton & Holt stock and recruitment function (BH) on the whole time series (1966-2012).

The use of a Bacoma 120/130 codend will also result in higher (8 %, 2017) catches compared to the Bacoma 120/105 (Ref) codend except for the initial year (Figure 4.7). A shift from

Bacoma 120/105 (Ref) to Bacoma 120/130 will introduce a decrease in catches the first year after the introduction.

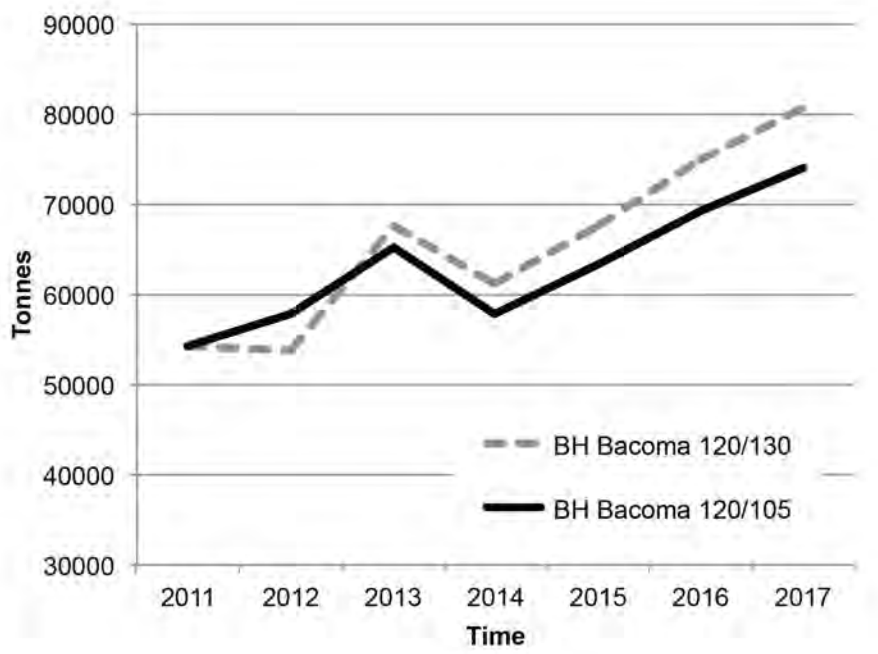


Figure 4.7. Estimated catches for the Bacoma 120/130 and the Bacoma 120/105 (Ref) codend using recruitment as estimated with by a Beverton & Holt stock and recruitment curve based on the whole time series (1966-2012).

The more selective Bacoma 120/130 codend also suggested that the number of fish per age class in the stock would increase (all ages, 1 %) compared to status quo selection (i.e. Bacoma 120/105 (Ref) codend, Figure 4.8). The results, even if they should be treated with caution as the forward projection is only based on Swedish data and only on trawlers, suggest that a shift to a more selective gear would result in a loss of catch the first year, but this is compensated quickly by an increase in catch weight at age and higher catch number of fish at age.

The medium-term forecast suggests that changed gear selectivity from Bacoma 120/105 to Bacoma 120/130 will only be slightly positive for the stock biomass, as a whole, even though the more selective gear will change the size distribution towards larger cod. From an catchability point of view for the fishery, a more selective gear would result in a short time loss (as in the example above) as the catch of smaller sized cod will be reduced but this drop in initial catch would be compensated after approximately 1 year, which suggests that increased selectivity can be positive on a longer time scale (see Cardinale and Hjelm 2012). The results derived from the medium term forecast is highly dependent on the weight at age and could be more positive if weight at age observed right now would increase and the opposite would happen if weight at age would decrease.

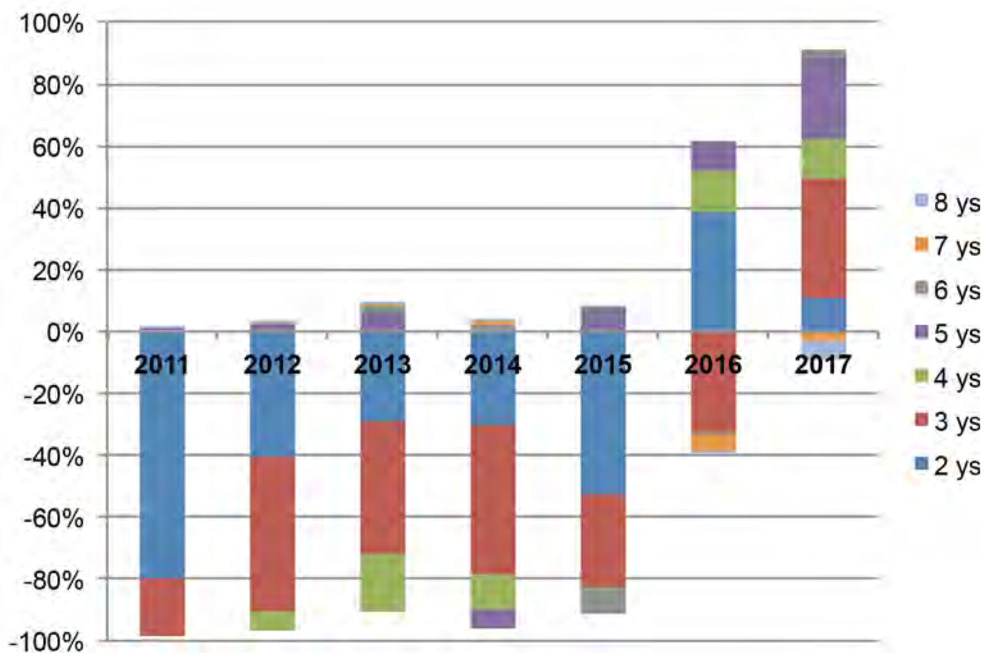


Figure 4.8. The difference in numbers at age in the stock for the Bacoma 120/105 (Ref) codend and the Bacoma 120/130 codend using recruitment as estimated with by a Beverton & Holt stock and recruitment curve based on the whole time series (1966-2012). A positive value (above 0%) suggests that the Bacoma 120/130 codend has resulted in more fish at age compared to a Bacoma 120/105 codend.

Conclusion

- If a discard ban would be introduced today, with current size distribution (period 2010) and with the current legislation (MLS 38cm, Bacoma 120/105 or T90 120 s8), it would result in decreased economic performance (about 20%, see Table 4.2).
- A reduced minimum landing size (MLS: from 38 to 35cm) is a possible way to minimize the negative economic effect of a discard ban.
- The most important single factor affecting the industry's economic performance was the size distribution of the cod stock, but management only indirectly influences this factor.
- The economic performance is in most cases lower when using selective gear compared to the Bacoma 120/105 reference trawl, but the differences in economic performance tends to be smaller when a discard ban is introduced.
- The industry's short term economic loss for increasing selectivity is smaller when the size distribution of cod is "good" (i.e. more large cod is present in the stock), irrespectively of a discard ban is introduced or not.
- The payback time in terms of catch of improved selectivity in the current state of the ecosystem is approximately a year given the current growth rate of the cod stock.

5 Concluding remarks

The Cod fishery in the Baltic Sea has a long history. In the 1980´s, the landings of this fishery peaked. During the last 40 years, the Baltic ecosystem has been strongly affected by human factors including fisheries, large scale eutrophication, and climate driven changes (Casini 2013). With this in mind and that the Baltic cod is living on the border of its distribution range, it is understandable that management of the cod stock in the Baltic is challenging. However, the species composition in this fishery, with few abundant species has some advantages from a management point of view compared to many mixed fisheries in other areas.

In this study, we have evaluated the present knowledge on cod discards and technical measures in the Baltic cod fishery in consultation with the industry. We here suggest different options including technical measures to reduce discards of undersized cod. Furthermore, we evaluate the impact of these suggestions on the economy of the fisheries concerned and on the development of the cod stock. We conclude (numbers refer to section in the report):

- (2.i) The gross part of the total discards in the Baltic cod trawl fishery is undersized cod, 59 % in weight in the eastern and 48 % in the western Baltic, followed by flounder and plaice.
- (2.ii) Even though the discard rates of cod in the Baltic are generally considered relatively low (about 10 %) compared to other areas, recent data suggests that discard rates are increasing (ICES/WGBFAS 2013).
- (2.iii) Using hotspot identification and persistence analysis we are able to assess how large potential area closures need to be to reach different management targets in protecting discard sensitive size classes of cod.
- (2.iv) Overlay analysis of potential area closures with the distribution of commercial size classes of cod, fishing effort and landings conflict significantly with hotspot areas of discard sensitive size classes of cod, indicating that an area closure will cause the effort to redistribute into adjacent fishing grounds and therefore increase the fishing effort in nearby areas if quotas (TACs) are the only measure to manage the fisheries.
- (3.i) There was minor difference in the selectivity comparing the experimental T90 codend with the reference Bacoma codend.
- (3.ii) The experimental Bacoma 120/130 increases selectivity for cod, flounder and plaice and reduces catches of individuals below MLS. Some reduction in cod catches above MLS, up to 42 cm in length is however expected. This codend is easy and cheap to construct.
- (3.iii) A full square mesh codend increase the selectivity of cod more than the Bacoma 120/130, causing a higher reduction and higher loss of cod below and above MLS respectively. There is no effect on flounder and plaice.
- (3.iv) The Freswind grid device gives a high reduction in catches of flounder and plaice and also some reduction in catches of cod up to 43 cm length.
- (4.i) If a discard ban were introduced today, assuming the size distribution of the 2010s (i.e. 2011-2013), the current legislation (MLS 38 cm, Bacoma 120/105 or T90 120 s8), and quota, it would result in about 20 % decreased economic performance.

- (4.ii) A reduced minimum landing size (MLS: from 38 to 35 cm) is a possible way to minimize the negative economic effect of a discard ban.

- (4.iii) The most important single factor, affecting the industry's economic performance, was the size distribution of the cod stock, but management only indirectly influences this factor.

- (4.iv) The industry's short term economic loss for increasing selectivity is smaller when the size distribution of cod is "good" (i.e. more large cod is present in the stock), irrespectively of an introduction of a discard ban or not.

- (4.v) The payback time in terms of catch of improved selectivity in the current state of the ecosystem is approximately one year given the current growth rate of the cod stock.

Recommendations

From these conclusions we recommend a combination of technical measures to further mitigate discards in the Baltic cod trawl fishery without jeopardizing the economy of the fisheries concerned.

- An increased selectivity (e.g. 130 mm diamond mesh instead of 105 mm codend with a Bacoma 120 mm window; Bacoma 120/130)
- A decreased minimum landing size/minimum conservation reference (MLS/MCRS) sizes to 35 cm.

By combining these two technical measures, a cost neutral solution (99 % of today economic outcome with todays technical measures) for the industry can be obtained and at the same time the catch of undersized cod can be reduced to 15 % of the number discarded today, (Table 5.1).

With these changes, the selectivity and the MLS/MCRS will be further separated compared to today, and would result in a significant reduction of discards in the trawl fishery of Baltic Sea. If the cod MLS/MCRS is kept at 38 cm, gear selectivity needs to be increased significantly in order reduce discards to <5 % given the current stock structure and will result in larger short term economic losses for the industry.

TableI 5.1. Relative economic performance and catch of undersized cod compared to the present situation (today) with no discard ban, MLS 38 cm and Bacoma 120/105 (Ref), in the Swedish Baltic cod trawl fishery.

Scenarios	Performance	Economic		Undersized catch	
	Gear/MLS	35 cm	38 cm	35cm	38 cm
Today	Bacoma 120/105 (Ref)	-	1.00	-	1.00
Discard ban	Bacoma 120/105 (Ref)	1.09	0.77	0.23	0.76
	Bacoma 120/130	0.99	0.74	0.15	0.55
	Full square 120	0.89	0.62	0.18	0.61
	Grid Bacoma 120/105	1.05	0.75	0.21	0.70
	T90 120 1-8	1.14	0.80	0.23	0.78

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Annex 1:

Interactions with the Baltic cod fishery

Interactions with the Baltic cod fishery

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Interactions with the Baltic cod fishery

There are three major ways of interactions with the Baltic cod fishery within this project; 1) a questionnaire about selectivity that was sent out in spring 2012 to active trawl fishermen fishing cod in the Baltic Sea, 2) a workshop on selectivity held in Karlskrona, Sweden, in May 2012 and 3) personal meetings with fishermen and organizations, especially before the commercial vessel sea trials in this project. A technical workshop, hosted by the European Commission, was also held in Brussels in September 2013 as a follow-up on the draft final report from the project.

1. Questionnaire

Aim and use

The aim of the questionnaire was to engage trawl fishermen in a dialogue with the project on selectivity, gear selection, discard patterns and management options to receive a picture of the occurring views, problems and potential solutions. The questionnaire was sent out in spring 2012.

A summary of the questionnaire was part of the background documents for the discussions at the workshop, held in May 2012, gathering fishermen, gear manufacturers and scientist to discuss how to minimize discard in the cod fishery in the Baltic Sea. The answers from Denmark were not available at the workshop, but are included in the results below. The answers from the questionnaire together with the discussions at the workshop and further on with the industry indicated which new codend designs to test in the sea trials.

Number of received answers to the questionnaire

There were 22 answers from Swedish fishermen out of 46 letters sent, 10 out of 130 from Polish fishermen, 7 out of 60 from German fishermen and 25 out of 133 from Danish fishermen.

Summary of the questionnaire
Most of the fishermen that answered have been fishing for a long time and a large amount of their fishing income is from the Baltic Sea. A clear difference in fishing grounds can be seen as Germany and Denmark are mostly or partly fishing in the western Baltic Sea but all the Polish and Swedish fishermen that answered are fishing in the eastern Baltic Sea.

Bacoma codend is most widely used (figure 1) and 68,6 % of all fishermen that answered said that this was the gear they use today. The reported pros and cons with the codends varied, but there are both handling and selectivity disadvantages that can be improved.

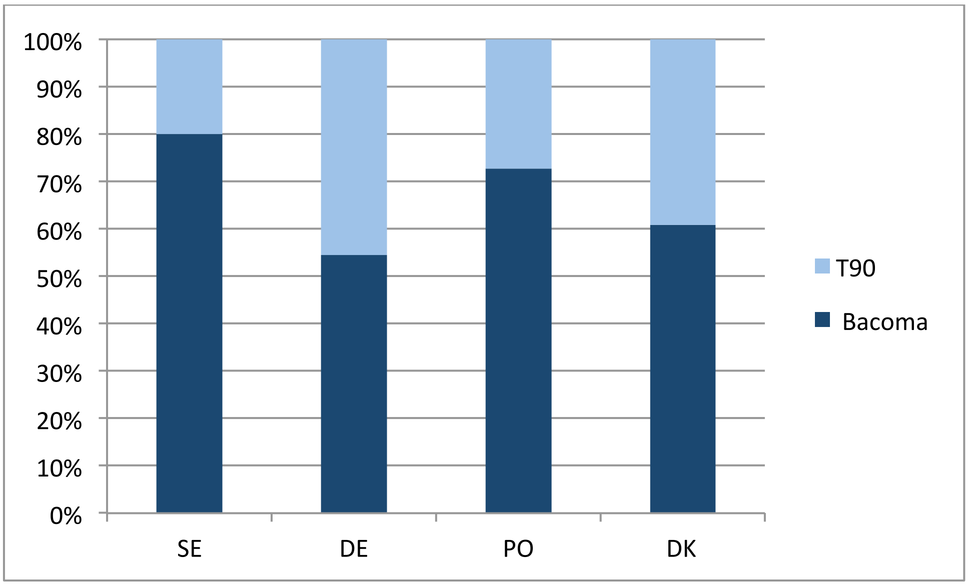


Figure 1. Percentage user of Bacoma and T90 respectively in each four countries.

The same number of responders said that discard will increase if all technical measures are removed as those who said that it will not increase.

The risk of catching discard was considered a little higher in winter and spring, but all times of the year could have more than average discard, depending on the fishing area. The question about *when* the risk of catching discard is more than average was perhaps not very cleverly put, but the answers show that it is not easy or even wise to generalize over such a large area. The marks in the map gave no clear patterns but only an indication that in “shelf areas” (shallower than in the area next to it, but not at any particular depth), discard could be more common.

An acceptable amount of discard, in weight, was for most of the responders between 1 and 10 % (figure 2). The estimated total discard caught was less than 5 % or up to 10 % for 63 % of the responders. Some estimate that their discard can be more than 20 %.

There are good possibilities of communication at sea and it is possible to receive information where the discard rich areas are. There are no general patterns if discard have increased or decreased over the last 5 years, probably due to differences in different areas of fishing. Most responders did not consider the cod to have increased in size over the last 5 years.

Management measures to decrease discard were also discussed during the workshop and a clear message from the industry representative was that permanently closed areas are not consider a good management strategy, but real-time closures, induced and governed by the industry itself, was an acceptable closure. About 40 % of the responders to the questionnaire said that they would like to have the possibility to initiate/contribute to real-time closures to prevent catch of undersized cod. Minimum landing size (MLS) could be important in management if it is decreased, but the views varied a lot.

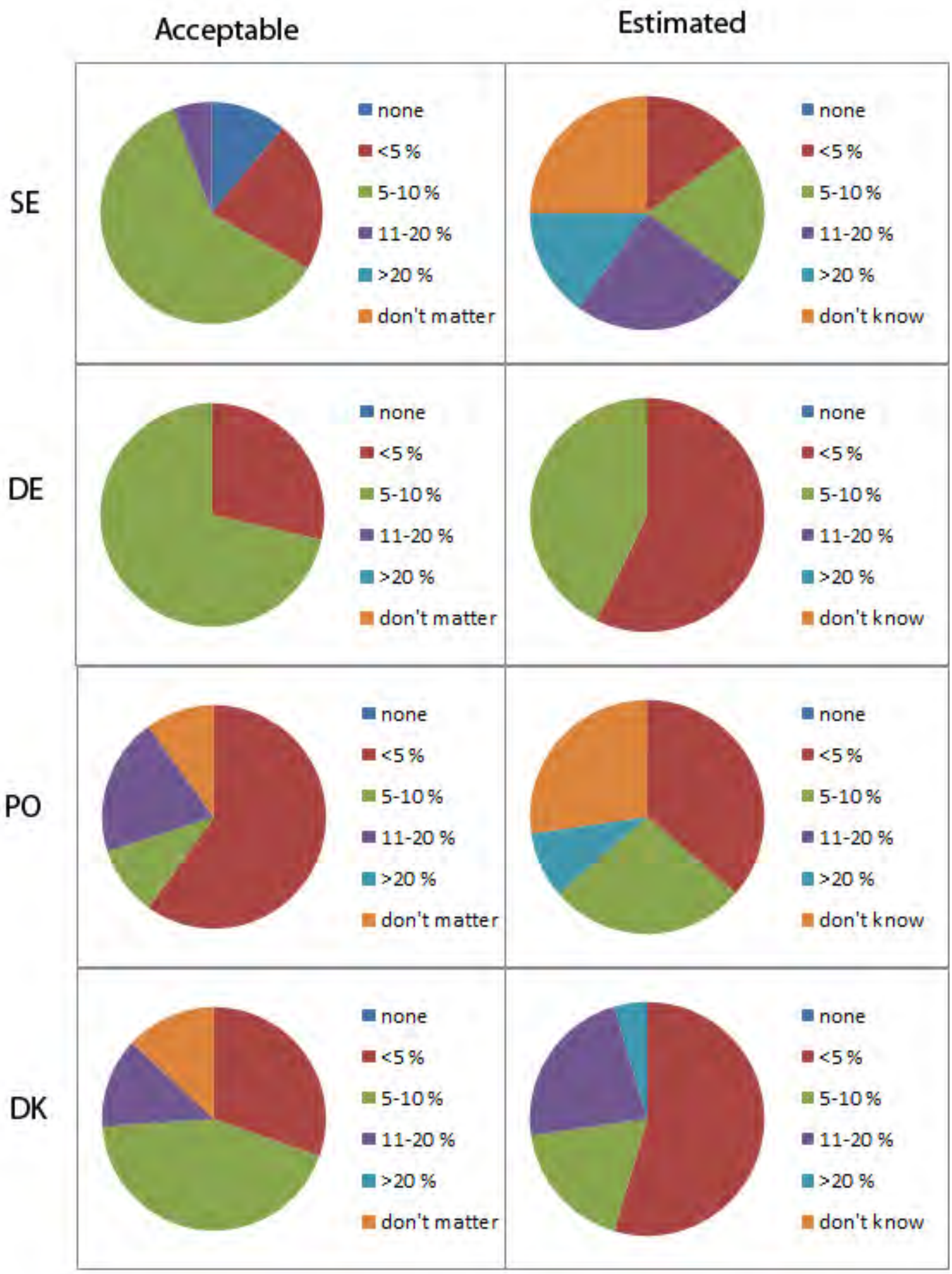


Figure 2. *What do you consider an acceptable discard, in weight? (Question 13) and How much would you estimate your total discard to be, in weight, during 2011? (Question 12)*

Answers to the questionnaire

Below the answers to the questionnaire are shown. N.B. For some questions, it was possible to give more than one answer and some questions were not answered in all questionnaires.

Background

1. How many years have you been fishing in the Baltic Sea?

	< 5	5-10	10-20	>20	Total
SE	1	1	6	13	21
DE	0	0	1	6	7
PO	1	0	3	6	10
DK	1	2	1	19	23
Sum	3	3	11	44	61

2. How much of your fishery income is from the Baltic Sea?

	>80%	50-79%	< 50	Total
SE	13	4	4	21
DE	4	3	0	7
PO	9	0	1	10
DK	11	5	6	22
Sum	37	12	11	60

3. Is the main part of your Baltic fishery in the eastern Baltic Sea (area 25-32), western Baltic Sea (area 22-24) or about the same in both areas:

	Eastern	Western	Both	Total
SE	21	0	0	21
DE	0	5	2	7
PO	9	0	1	10
DK	11	13	2	26
Sum	41	18	5	64

4. Do you mainly fish cod with trawl in the Baltic today?

	Yes	No	Total
SE	20	1	21
DE	7	0	7
PO	8	2	10
DK	19	8	27
Sum:	54	11	65

Gear

5. Which gear (codend) do you use today?

	Bacoma	T90	Total
SE	18	5	23
DE	5	4	9
PO	8	3	11
DK	14	9	23
Sum	45	21	66

6. Which gear have you used in year 2000-2010?

	Diamond mesh	Swedish window	Danish window	Bacoma window	T90	Don't know
SE	2	6	3	19	4	0
DE	2	1	0	5	3	2
PO	2	0	0	5	3	3
DK	3	0	6	19	0	0
Sum	9	7	9	48	10	5

7. What are the pros and cons with different codends in terms of discard?
This question did not have premade check answers. Personal views and ideas were received and some more were added at the workshop. A summary of the comments are shown below:

- Bacoma releases too much consumption fish
- T90 releases too much consumption fish, when the catch is low
- Bacoma has a better selectivity and thus less discard
- Both trawls are wrongly constructed
- Both trawls are working poorly
- None of them has a selectivity good enough
- Diamond codend was an optimal codend, without high discard
- Bacoma and T90 codends increase selectivity of cod fishing
- Small discard of undersized cod is observed, selectivity of Bacoma codend is sufficient
- There is no discard
- Selection is too high
- High discard reduction
- Meaningful selectivity is only to be seen at T90
- Only Bacoma used, therefore no difference known between Bacoma and T90
- T90: less discards
- Relative good selectivity with Bacoma, if not too much flatfish in codend or total catch size not too big or fish “towed to death”
- Advantage with T90: less small flatfish
- Disadvantage with T90: large cod (>40cm) escape easily
- Advantage with Bacoma: not many large cod (>40cm) escape
- Disadvantage with Bacoma: many small cod in short time, discards higher than T90
- Old Bacoma best
- The amount of small cod matters, if there are a lot in the area it gives a lot in the trawl
- More small cod when mesh size increased to from 120-127 mm.
- Bacoma too thin, it kills and decreases the quality of the fish

8. What are the pros and cons with different codends in terms of practical handling?

This question did not have premade check-answers. Personal views and ideas were received and some more were added at the workshop. A summary of the comments are shown below:

- None of them causes problems
- Bacoma breaks easily, hard to repair
- T90 is easier and cheaper to repair
- Bacoma is working poorly and is difficult to repair
- No difference, if you use sensors,
- No pros, both are working poorly
- Apply of Bacoma and T90 codends decrease discard
- Disadvantage of Bacoma is weakness of the window netting, mesh opening
- T90 is easier to repair and more stable in abrasion;
- In the eastern Baltic Sea the meshes are too large (127-128 mm), in western Baltic Sea mesh size is OK
- Difficult to fix Bacoma and T90 codends properly
- T90 is easiest to handle
- Bacoma too difficult to repair
- No difference between both cod ends
- T90: many fish sticking in the net.
- Advantage T90: cheaper and easier to build/repair
- Disadvantage Bacoma: material/meshes become narrow quite fast (shrinkage)

9. Will discard increase if all technical measures are removed?

	Yes	No	Don't know	Total
SE	14	6	1	21
DE	1	5	1	7
PO	5	2	3	10
DK	7	13	1	21
Sum	27	26	6	59

Patterns of discard in time and space

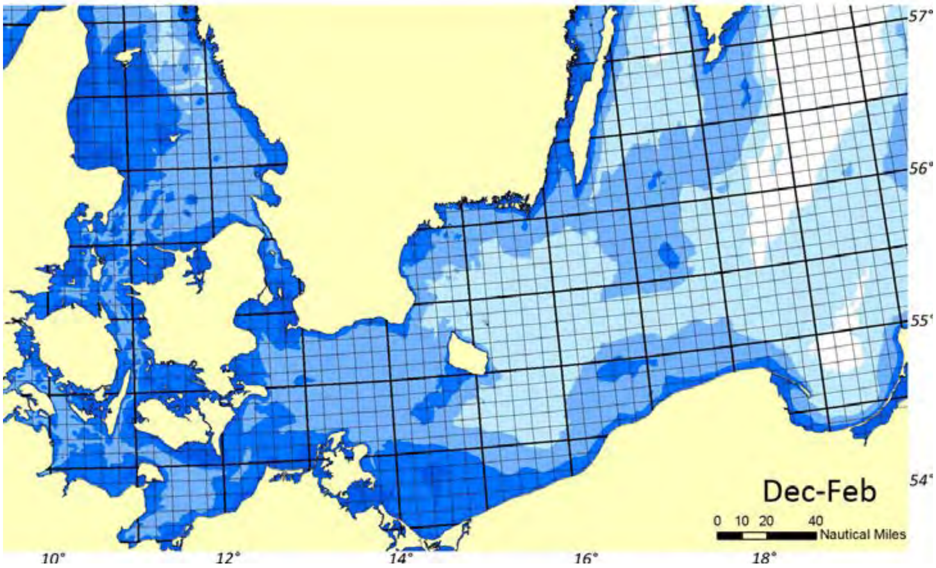
10. Which time of the year do you think the risk of catching discard is more than average? In the winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug) or in the autumn (Sept-Nov)?

	Winter	Spring	Summer	Autumn	Total
SE	10	3	1	2	16
DE	2	2	1	1	6
PO	1	5	2	1	9
DK	7	7	1	6	21
Sum	20	17	5	10	52

Additional comments:
- in no specific season
- it depends on schooling of cod
- depends on fishing area.

11. Please mark a maximum of 10 squares per map (time period) that according to your experience are the areas with most discard of undersized cod.

A map was presented for 4 different seasons (3 month time intervals).



The analysis of the answers is not straight forward and gives no clear picture. It seems like cod discard is perceived to be more common in shelf areas.

12. How much would you estimate your total discard to be, in weight, during 2011?

	<5 %	5-10 %	10-20 %	>20 %	don't know	total
SE	3	4	5	3	5	20
DE	4	3	0	0	0	7
PO	4	3	0	1	3	11
DK	12	4	5	1	0	22
sum	23	14	10	5	8	60

13. What do you consider an acceptable discard, in weight?

	none	1-5 %	5-10 %	11-20 %	don't matter	total
SE	2	4	11	1	0	18
DE	0	2	5	0	0	7
PO	0	6	1	2	1	10
DK	0	7	10	3	3	23
sum	2	19	27	6	4	58

14. How do you receive information on the occurrence of large amounts of juvenile cod in a fishing area?

	colleagues	own experience	fishing there	Other	Total
SE	21	17	13	0	51
DE	4	5	5	1	15
PO	8	5	4	0	17
DK	13	16	9	3	41
sum	46	43	31	4	124

15. Can you – by experience – foresee which area to avoid fishing in, due to large amounts of discard?

	Yes	No	total
SE	17	4	21
DE	4	3	7
PO	6	5	11
DK	16	5	21
sum	43	17	60

16. Do you think that the discard has been reduced over the last 5 years?

	Yes	No	don't know	total
SE	6	9	6	21
DE	6	2	0	8
PO	4	5	1	10
DK	12	8	5	25
sum	28	24	12	64

17. Do you think that the mean size of the cod has increased over the last 5 years?

	Yes	No	don't know	total
SE	5	13	3	21
DE	3	5	0	8
PO	4	5	1	10
DK	5	16	2	23
sum	17	39	6	62

18. Do you think that the cod caught over the last 5 years is thinner? (A question only given to Swedish fishermen)

	Yes	No	don't know	total
SE	14	3	3	20

Management

19. Which management measures are important?
a) Decrease MLS (Minimum Landing Size):

	important	some importance	Not important	Don't know	tot
SE	6	6	6	3	21
DE	5	2	0	0	7
PO	3	3	0	4	10
DK	12	1	8	2	23
sum	26	12	14	9	61

b) Increase MLS:

	important	some importance	Not important	Don't know	tot
SE	0	3	10	3	16
DE	0	0	7	0	7
PO	3	4	0	3	10
DK	2	4	9	2	17
sum	5	11	26	8	50

c) No MLS:

	important	some importance	Not important	Don't know	tot
SE	4	3	6	5	18
DE	4	0	1	1	6
PO	3	2	0	5	10
DK	4	4	3	4	15
sum	15	9	10	15	49

d) Increase selectivity further:

	important	some importance	Not important	Don't know	tot
SE	13	6	0	2	21
DE	2	1	3	1	7
PO	4	1	2	3	10
DK	1	5	9	2	17
sum	20	13	14	8	55

e) Permanently closed areas:

	important	some importance	Not important	Don't know	tot
SE	2	1	12	3	18
DE	1	1	4	1	7
PO	3	1	2	4	10
DK	0	1	16	2	19
sum	6	4	34	10	54

f) Temporally closed areas:

	important	some importance	Not important	Don't know	tot
SE	4	3	11	1	19
DE	3	4	0	0	7
PO	6	1	1	2	10
DK	1	4	15	1	21
sum	14	12	27	4	57

20. Would you like to have/use the possibility to initiate/contribute to a real-time-closure of fishery in an area, to prevent catch of undersized cod?

	Yes	No	Don't know	total
SE	3	9	8	20
DE	6	0	1	7
PO	7	2	1	10
DK	6	13	1	20
sum	22	24	11	57

2. Workshop on improved selectivity in the Baltic Sea demersal trawl fisheries

Aim

The aim of the workshop was to set up a platform for stakeholders to form an opinion on the feasibility of the solutions proposed and to communicate with the industry about experiences and preferences and to provide concrete response with regard to further modifications as well as to challenges and limiting factors. The workshop discussions should allow refining of the solutions to be further tested within the project.

Invitation, setting and participants

The workshop was held in Karlskrona, south east Sweden on the 24-25th of May, 2012. Fishermen and gear technicians from Poland, Germany, Denmark and Sweden were invited either through personal invitations or through their fishing organizations. The invitation was distributed in cooperation with the Baltic Sea Regional Advisory Council (BSRAC), addressing also fishery representatives from their members.

There were 31 participants at the workshop from 19 different organizations, eleven of them directly fishery related and five were research institutes (of which four were project partners).

Agenda and discussions

Three opening talks were made to introduce all participants to the results from a) the desk top study on discard patterns in time and space (presented under section 1 in this report), b) the answers from fishermen to the questionnaire about discard patterns, gear selectivity and management options in this report. The variety in opinions found in the answers in the questionnaire was also found at the workshop.) c) the results of the selectivity tests made so far.

After this introduction two opening talks for the discussion were made by:

Michel Andersen from the Danish Fishermen's Association gave a talk about the fishermen's opinion on criteria for a good technical solution:

- emphasizing that there may be many possible solutions working together
- scientific solutions should be options, not mandatory regulations
- there is not one view from the fishermen as they have different view depending on their perspective
- temporarily closed areas could be useful if used when and where it is needed but the industry should be involved in the decision of when and where.

Dominic Rihan from the European Commission informed the audience about the reformation of the Common Fishery Policy. He stated that a new approach is needed because the technical regulations are too complicated. The new approach should:

- contribute to minimized discard
- be based on standards and principles rather than be prescriptive and complex
- have a scope for regionalization, flexibility and dynamic

- provide incentives for fishing responsibility by involve stakeholders and give greater responsibility to the industry
- provide stability by multiannual plans.

The main aim of the workshop was to have a productive dialogue. After the introductory talks on day one, the focus lay on group discussions on the need for better selectivity in the light of changes in management; I) challenges caused by a new CFP II) main problem(s) to be solved and III) specification of "better" selectivity. Each chair of the groups in plenum presented the main points from the group discussions. As a basis for the proposal and evaluation of potential technical solutions, some important needs were identified during the discussions:

a) Proposed gear should have a rather steep selection curve and low in-between haul variation, since a flat and not well-defined selection curve potentially results in high discard rates and high loss of marketable fish.
b) Proposed gear should ideally be simple and cost efficient. One of the important points for critique regarding the BACOMA-design is the high price of the used netting material.
c) Proposed gears have to be easy to handle, especially given the size distribution of vessels in the Baltic Sea, including many small vessels.
d) Proposed gear should be adopted to MLS (if there is any)
e) Proposed gear should take into account other species

Other views, challenges and problems discussed in plenum:

- How to better involve the industry, give the responsibility back to the fishery and how to bring the industry and science together.
- The problem to control a discard ban and manage a catch quota system. CCTV monitoring and/or fully documented fishery have problems with the personal integrity of the fishermen- Cameras are like Big Brother.
- What to do with unallocated by-catch and choke species.
- The need of transferrable fishing concessions and multiannual plans for stability.
- Take away the Western and Eastern Baltic stock division.
- Regionalization, how specific should the common fishery policy be?
- The gear regulations should take into account the boat size and motor strength.
- Is discard a major problem in the Baltic?
- Start all over with gear construction. The ones today are all bad.
- Minimum landing size is a hot potato.

During day two, the focus was on technical gear solutions; I) suitability of different proposals from fishery and II) proposal for further work. Before the discussions in the morning started Daniel Stepputis and Bent Herrmann introduced different suggested technical solutions, Waldemar Moderhak presented studies of performance and construction of T90 and Krzysztof Stanuch presented an envelope-type construction of a codend.

During the discussion, concerning possible technical solutions to decrease discard, many suggestions arouse; Could you stimulate the fish to escape? Should focus be only on the codend selection, not the "belly"? Problems with aging of the gear was discussed, improvements of existing gear and development of new ones, stability of selectivity under different conditions, problems with testing of new gear due to detailed regulations how a trawl is allowed to be constructed, good materials to produce selection panels of, sorting grids, the earlier you select out juvenile cod the better they survive, could you document with a camera to see how the gear and catch behave, problems with making patented solutions mandatory, etc.

Eight suggestions for “better” selectivity were discussed in more detail:

1. An escape-improving device, by Vilnis Ulups, to mount in front of the codend (belly section), to sort out unwanted flatfish (flounder).
2. Optimize the size of the lower BACOMA panel, with a bigger mesh size.
3. An envelope-type codend suggested by Krzysztof Stanuch.
4. Plastic panels of different shape (“Carlsen-trawl”).
5. Sorting grid.
6. Swedish exit window (side panel).
7. Back to diamond mesh.
8. T90 (optimized).

An attempt to summarize pros and cons in a table of the suggested solutions was made (Table 2), and different criteria for why to choose each solution were listed. Some of the participants had to leave earlier, many of the criteria were difficult to decide directly if they were good or bad and some statements had to be checked or further discussed. There was thus a lot of constructive work done at the workshop but some left to continue with.

Table 2. Solutions suggested at the workshop for better selectivity and criteria that they should fulfil. “+” means positive, “-“ means negative, and “?” means not enough information to decide. See text above for description of the eight different suggestions.

	suggestions							
criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Selection Range down	+?	+?	+?	?	?	?	-?	+?
stability	+?	+?	+?	?	+?	+?	+?	+
less flounder	+	+?	0	?	0?	0?	+ (small)	-?
easy to repair	+	+	1	-	-?	+?	+	+
within legislation	+	-?	-	-	-	-	-	-
easy handling	?	0	+?	?	-	+	+	+
Acceptable by industry	?	-	+	?	-	0+-	?	+

During the workshop, a number of interesting solutions for more selective gears were presented and discussed (Table 2 shows the eight suggestions that were discussed in more detail). The suggestions in table 2, together with other suggestions during the workshop, was further evaluated by the project team before 4 designs was picked for the commercial vessel sea trial.

The full agenda of the workshop is included below.

Agenda at the workshop on improved selectivity in the Baltic Sea demersal trawl fisheries, 24-25 of May in Karlskrona, Sweden

Thursday 24 May

08.30-09.00	Registration for workshop at Blekinge museum
09.00-09.15	Welcome and introduction to the project and the workshop *Daniel Stepputtis – vTI*
09.15-10.00	Discards in the Baltic Sea – where and when *Hans Nilsson – SLU*
10.00-10-30	*Coffee*
10.30-10.55	Fishermen's opinion - based on questionnaire *Malin Werner - SLU*
10.55-11.40	Overview of the performance of alternative cod end designs tested so far *Bent Herrmann - DTU, Daniel Stepputtis – vTI,*
11.40-12.00	Fishermen's opinion on criteria for a good technical solution *Michael Andersen - BSRAC*
12.00-13.00	Lunch
13.00-13.30	Introduction on foreseeable management changes in the new CFP *Dominic Rihan – EC*
13.30-15.30	Group discussions on the need for better selectivity in the light of changes in management - Challenges caused by new CFP - Main problem(s) to be solved - Specification of "better" selectivity
15.30-16.30	Summary of group discussions and Plenum discussion
18.00	Dinner

Friday 25 May

09.00-09.30	Three short introductions on gear solutions *Bent Herrmann - DTU, Daniel Stepputtis – vTI* *Presentation of T90 by Waldemar Moderhak,* *Presentation by Krzyzstof Stanuch, suggested cod end modification*
09.30-12.00	Group discussions on technical gear solutions - Suitability of different proposals from fishery - Proposal for further work
12.00-13.00	Lunch
13.00-15.00	Summary of group discussions and plenum discussion

3 -Technical workshop "Selectivity in Baltic Cod Fisheries Workshop" hosted by European Commission (EC), 4 September 2013

After the draft final report of the project was presented, a one-day technical workshop, hosted by the EC, was held in Brussels on the 4th of September 2013. The workshop was moderated by Mr Martin Pastoors and is reported by the EC. The project held 3 presentations at the workshop (Patterns and causes of discarding in the Baltic Sea and The selectivity options identified and tested in the Lot1 project). After this workshop participating stakeholders were invited to submit written comments on the project draft report. Comments from two stakeholders were received and the project has incorporated the comments as far as possible into this final report.

Annex 2:
Modelling spatial and temporal distribution of discard sensitive cod and fishery effort

Modelling spatial and temporal distribution of discard sensitive size classes of cod, commercial size classes of cod and fishery effort

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Introduction

The obvious method to reduce unwanted by-catch and discards is to diminish the total fishing effort, however, more attractive to the fishing industry is generally technical measures e.g. to introduce more selective gears. Closed areas, both permanent and temporal, are a potentially useful management measures to reduce unwanted by-catch and discards if aggregations of discard sensitive species or size groups of fish can be identified. The disadvantage, however, of any regulations is that the simultaneous reduction in catch per unit effort and/or size of the target species, generally results in a loss to the fisher in the short term (e.g. Cardinale and Hjelm 2010). A crucial challenge for the managers is thus to minimize this loss in the short term, while still achieving the management goals set-up in the long term.

In this context, knowledge of the spatial -temporal distribution of the different life stages of fish populations, and the spatial - temporal use of the fishing grounds by the fishing fleet is crucial to enhance the understanding of why and where species are caught and discarded. Taken together this knowledge can be used to predict the effects of closed areas to and reduce unwanted by-catch and discards of targeted species, as well as to protect other components of the ecosystem, i.e. sensitive habitats and non-commercial or protected species.

The Baltic cod fishery provides an excellent case for investigating the potential of spatial management using closed areas. This fishery dates back to the 6th century but the cod stock has been exploited intensively only since the 1950s (MacKenzie et al. 2002, Bagge et al. 1994). The Baltic cod fishery is nowadays dominated by trawling but hooks and gillnet are also common. The Baltic cod trawl fishery is unique in the sense that undersized cod, which are discarded, dominates the catches (48-59%) and that the number of species in the catches are very few (3-5 species represents >98% of the biomass) due to the low diversity of the low saline Baltic Sea ecosystem. Even though discard rates of cod is relatively low (ca. 10%) it can vary considerably and was estimated in 2012 to 25% (ICES 2013). The annual variability in discard rates relates mainly to year-class strength.

Technical conservation measures have a relatively long history and have focused on gear regulations aiming at reducing the catch of young cod (Madsen 2007). During the last two decades gear regulations have changed several times concerning mesh size and exit panels. Despite all these regulations the problem of discards in the trawl fishery remains and is considered a serious problem.

In the present study, we analysed the spatial distribution of cod and the cod trawl fishery exploiting Western and Eastern Baltic Sea cod stocks (i.e. stocks inhabiting ICES subdivisions (SDs) 22- 24 and SDs 25-32, respectively) to predict the efficiency of area closures to protect juvenile cod and the impact of these closures on the activity of the trawl fishery. We use Baltic international trawl survey (BITS) data to model fish distribution and Vessel Monitoring System (VMS) combined with logbook information to map fishing effort and landings. Identified persistent hot-spot areas of discard sensitive size classes of cod (30-37 cm) under different management goal scenarios were then overlaid on the distributions of commercial size of cod (37+) and trawl fishery effort to evaluate the performance of the closures and the potential cost to the fishery.

The analysis is composed by the following parts:

- Modelling the spatial distribution of three different size classes cod (30-37, 38-48 and >48cm)
- Estimate the hotspots areas of discard sensitive size classes of cod (30-37cm)
- Overlay analysis of the hot-spot areas of discard sensitive (30-37cm) and commercial size classes of cod (38-48 and >48cm)
- Overlay analysis of the hot-spot areas of discard sensitive classes of cod (30-37 cm), the fishing effort and catch distributions of the commercial trawl fleet in the Baltic Sea
- Following the overlay analysis, by year and quarter, quantify the efficiency of the area closure in protecting discard sensitive size classes of cod and the cost to the fishery due to reduction in catch opportunities together with the potential reduction of the realised effort.

Material and Methods

Data collected

Data on the spatial and temporal distribution of cod were collected on board of the Baltic international trawl survey (BITS) and extracted from the ICES DATRAS database for the period 2001 to 2011. Data on the abundance of cod by length classes (i.e. 2 cm) were standardised by using conversion factors for respectively combination of length class and gear used in the BITS survey during the time period. Area and stock (i.e. Western and Eastern Baltic cod stocks) dependent length-weight relationships were used to convert cod abundance in biomass (WGBIFS, 2007). Length distribution was then divided into one size class below the minimum landing size (MLS) of 38 cm and two size classes above it. The first size class corresponds to the most discard sensitive size classes (i.e. 30-37 cm) of cod in the Baltic, the second (i.e. 38-48 cm) corresponds to the EU commercial category 5 (which constitutes the bulk of the catches in the Baltic trawl fishery) and the third size class (>48cm) corresponds to EU commercial categories 4 and above.

Modelling of the spatial distribution of cod

The spatial distributions of the three size classes of cod during the first and fourth quarter of the year for the period 2001-2011 were analysed and modelled using a geostatistical approach. Catch per unit of effort (CPUE) in number per hour ($n \cdot h^{-1}$) of cod was used as response variable for the 30-37 cm size class, while CPUE in biomass per hour ($kg \cdot h^{-1}$) of cod was used as response variable for the 38-48 cm and >48 cm size classes. This allows for a better comparison with commercial data, which are expressed in numbers for the discard fraction (i.e. 30-37 cm) but in weight for the fish landed (i.e. 38+).

A kriging technique, namely regression kriging, was adopted for this purpose, and the following general model structure was used:

(1) $$Y(s_i) = \mu(s_i) + \varepsilon(s_i)$$

where $Y(s_i)$ is the observed value at location s_i, $\mu(s_i)$ is the mean effect or large-scale variation, and $\varepsilon(s_i)$ is the error part of the model or small-scale variation (Cressie 1993). A Box-Cox transformation was applied to achieve normality in the data. The deterministic part of variation in the distribution of cod (mean effect) was described by a second order polynom on the depth covariate measured in each location at the time of sampling. The spatial dependency in the error part of the model was then analyzed using semi-variograms (Rossi et al. 1992). Given a variable s measured at several locations identified by the subscript *i*, the sample or empirical variogram γ(*h*) at a specific lag-distance *h*, is estimated as the semivariance among all pair of points *n* separated by the distance *h*:

(2) $$\gamma(h) = \frac{1}{2\mathrm{n}(h)} \sum_{i}^{n(h)} \left[y(s_i) - y(s_{i+h}) \right]^2$$

The quantities $y(s_i)$ and $y(s_i + h)$ are the abundance estimates at the two sides of the distance vector (*h*). We found an increasing semivariance estimate over increasing distances, which indicates a spatial correlation among observations. Visual inspection of the empirical semi-variograms suggested that the exponential theoretical model was appropriate to describe the spatial dependency of cod CPUE, hence variogram parameters where estimated using ordinary least square.

The final kriging estimates were done for each length class, quarter and year, on a 3 km x 3 km estimation grid. Depth information associated to the grid was available from the Balance project (http://balance-eu.org/about_us/index.html).

All the geostatistical analyses were performed using the library geoR (Ribeiro and Diggle 2001) of the R statistical software (R Development Core Team 2010).

Hotspot analysis

The recognition of the areas which are potentially most sensitive to the practice of discarding was based on the identification of those areas with the highest concentration of discard sensitive size classes of cod (30-37cm). For this purpose, we used a hotspot analysis on the modelled distribution of cod in the 30-37 cm size class (Figure 1 and 2) to identify where discard sensitive size classes of cod aggregate during the investigated time period. Hotspots areas were identified using three arbitrary global thresholds of 25%, 50% and 75%, which represents a wide range of conservation and management target levels (Bartolino et al. 2011). In practice, these target levels are aiming to identify those areas with the highest concentration of discard sensitive cod which include in each season and year 25%, 50% and 75% of all the estimated number of discard sensitive size groups of cod (30-37 cm) in the distribution area of the stock.

Successively, the temporal stability of these hotspot areas was investigated by calculating the persistence index (Colloca et al. 2009). This index (I_i) describes the relative persistence of a given cell *i* as a hotspot, which indicates how often any given location is selected for its high concentration of discard sensitive size classes of cod within the examined time series. Let $\delta_{ij}=1$ if the grid cell *i* is selected as hotspot in year *j*, and $\delta_{ij}=0$ otherwise. We computed I_i as follows:

(3) $$I_i = \frac{1}{n} \sum_{j=1}^{n} \delta_{ij}$$

where *n* is the number of years considered in the analysis. I_i ranges from 0 (cells never selected as hotspot) to 1 (cells always selected as hotspot). Finally, a polygon was calculated around those areas that obtained an I_i score ≥0.50, which in practice corresponds to those areas/grid cells selected as hotspot for at least 11 times over the 22 time steps (2 quarters x 11 years) used in the analysis (Figure 9).

Modelling of the spatial distribution of fishery landings and effort

Typical trawling speeds are selected from the VMS records, and logbook information on catches, species and vessel characteristics are associated to the VMS records using reported fishing time. This means that the total catch of a trip is allocated equally to each position within that trip. The fishing effort is calculated as the sum of pings times the vessel engine size (kW). For each trip, a métier (fishing activity class) is assigned through combinations of specific landings composition and/or specific gear metrics such as trawl type and mesh size (see Bastardie et al., 2010 and Gerritsen and Lordan 2011 for further details and validity of the method).

Recently, an R-package*, vmstools,* has been developed (Hintzen *et al*. 2012) to facilitate the merging procedure. For the purpose of this study, the highly spatially refined landing and effort data were compiled at the national level, either by the use of *vmstools* (Bastardie et al 2010) or by similar algorithms (Gerritsen and Lordan, 2011) and aggregated on a 3 x 3 nautical miles grid to monthly values of cod landings, total landings and effort (in kW hours).

Results

Spatial distribution of cod

The BITS survey dataset covers XX hauls collected over the 11 years period in the western and eastern Baltic Sea. The final kriging estimates showed significant effects and the spatiotemporal maps of cod distribution in respective size classes 30-37cm, 38-48cm and >48cm are shown in figures 1-6. All three size groups showed patchy distributions of cod and areas of higher CPUE are evident from the figures as well as from the raw data, indicated by the relative size of the bubbles in the plots (Fig. 1-6).

Distribution and persistence of hot-spots of discard sensitive cod

The hotspot analysis of the modelled distribution of the discard sensitive size classes of cod also shows a rather patchy distributions with a large variation of the hotspots areas within and between years (Fig. 7 and 8).

The persistence analysis of the hotspots using the three defined thresholds of 25%, 50% and 75% shows a stable pattern (I_i score ≥0.50) with high concentration of the discard sensitive size class in the Hanö bay and around the Bornholm basin. The persistence analysis also indicated a wider distribution and a decreasing importance of the part west of Bornholm in quarter 4 (Fig. 9).

Spatial distribution of fishery landings and effort

The landings and fishing effort are generally distributed around the Bornholm basin, with the highest efforts to the east of the basin, and along the tip of the south-eastern coast of Sweden (Fig. 11 and 12).

Overlay analysis

Following visual inspection of the persistence pattern it was concluded that the main hotspots overlapped for quarter 1 and 3. Accordingly, a scenario of area closures using the three cconservation and management target levels (i.e. 25, 50 and 75%) was evaluated based on data from quarter 1 and 4 combined. The areas identified as hot-spots more than 50% of the time (i.e. green polygon area in Fig. 9) were used to evaluate the efficiency of area closure in protecting discard sensitive cod. Also the conflict of a closure with the commercial size classes of cod was evaluated analysing the spatial distribution of the landings of the trawl fleet as identified from the VMS and logbook information. The scenario was evaluated by estimating the fraction over time of size class of fish or landings, located within the closure as estimated by the modelled distribution.

Box plot analysis of the different scenarios shows very low efficiency of the closure (i.e. median =0.18% in numbers of discard sensitive cod) to protect cod between 30-37 cm using a management target of 25% for persistent hot-spots. On the other hand, using management targets of 50 and 75% increased the efficiency significantly, with 15 and 57% in numbers of discard sensitive cod being potentially protected, respectively (Fig. 10 a). There is a large interannual variation of the location of the hotspots, which could explain the low efficiency in protecting discard sensitive cod using the smallest target (25%), i.e. protecting a small area will be inefficient due to high temporal variability in the cod spatial distribution.

Overlaying the areas closure individuate by the different management targets with the distribution of the commercial size classes of cod and fishery information of the landings and effort show a considerable overlap. Area closures corresponding to the management targets of 50 and 75% (i.e. 5 and 20% of the distribution area) would conflict with the spatial distribution of effort by 27 and 63%, and landings by 20 and 56%, respectively (Fig. 10 b).

Discussion

Conclusions from the analysis of the distribution of discard sensitive cod, hot-spot areas and the persistence analysis can be summarised as follows:

- The modelling approach allows us to identify hot-spots areas with regular occurrences of different size classes of cod based on scientific survey data.
- Using hot-spot identification and persistence analysis we are able to assess how large potential area closures need to be to reach different management targets in protecting discard sensitive size classes of cod.
- Discard sensitive size classes of cod in the Baltic are persistently concentrated to certain areas i.e. the Hanö bay, and around the Bornholm basin. The analyses also indicate a wider distribution and a decreasing importance of the part west of Bornholm in quarter 4.

Overlay analysis of potential area closures with the distribution of commercial size classes, fishing effort and landings conflict significantly with hot-spot areas of discard sensitive size classes of cod indicating that an area closure will cause the effort to redistribute in adjacent fishing grounds and therefore increase the fishing effort in nearby areas if quotas (TAC:s) are the only measure to manage the fisheries.

The further step in evaluating the potential for area closures to reduce discards of cod below the MLS would be to use a systematic conservation planning approach (Margules and Pressey 2000, Ball et al. 2009). This will involve setting quantitative management goals for reducing discards of cod and account for the costs i.e. lost fishing opportunities, reduction of unwanted by catch of sensitive species, minimisation of fuel costs, etc). Such an analysis will be able to identify areas with discard sensitive cod where costs of the effort displacement are minimised.

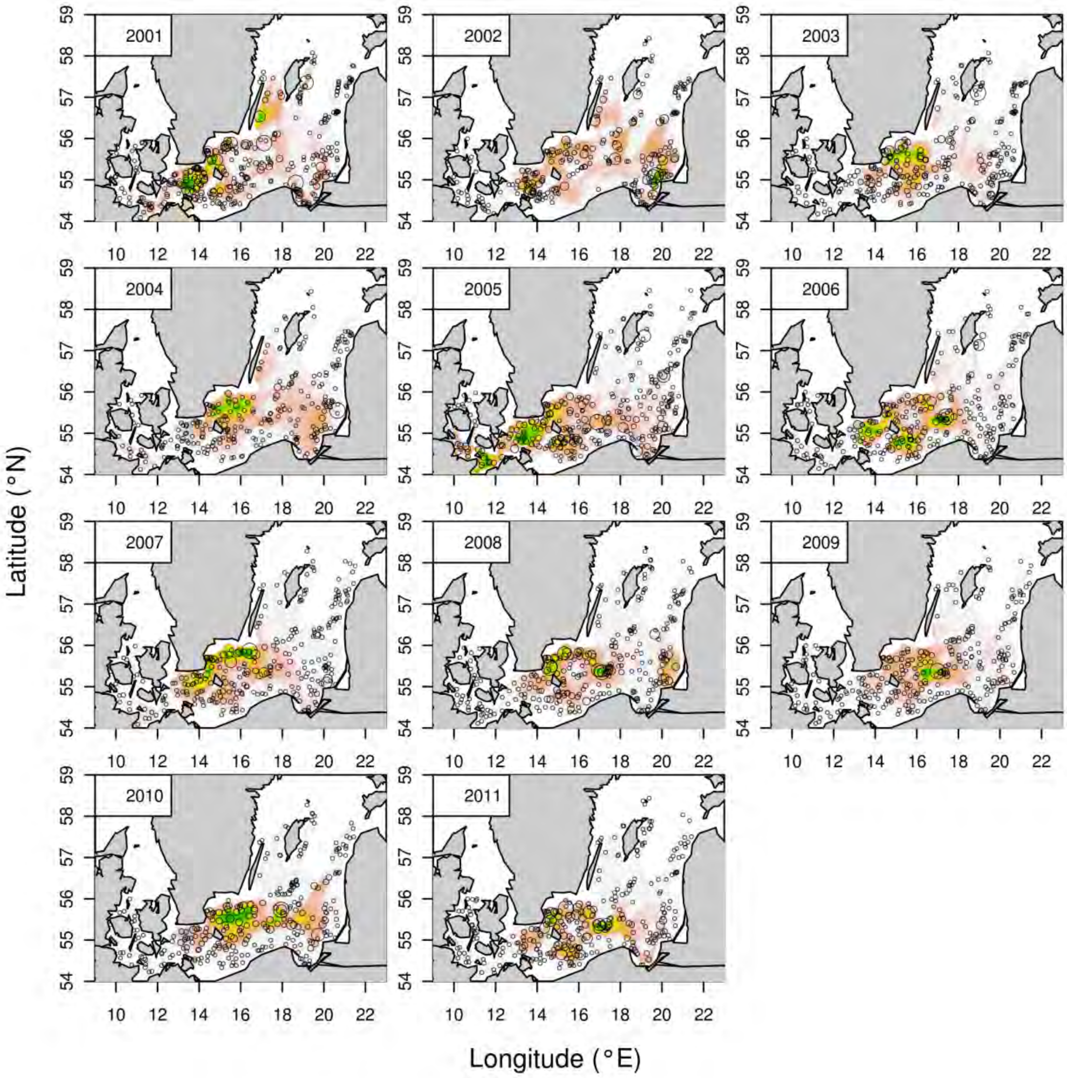

Figure 1. Distributions of discard sensitive size classes of cod (30-37cm) in the Baltic Sea during quarter 1 (February to March) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

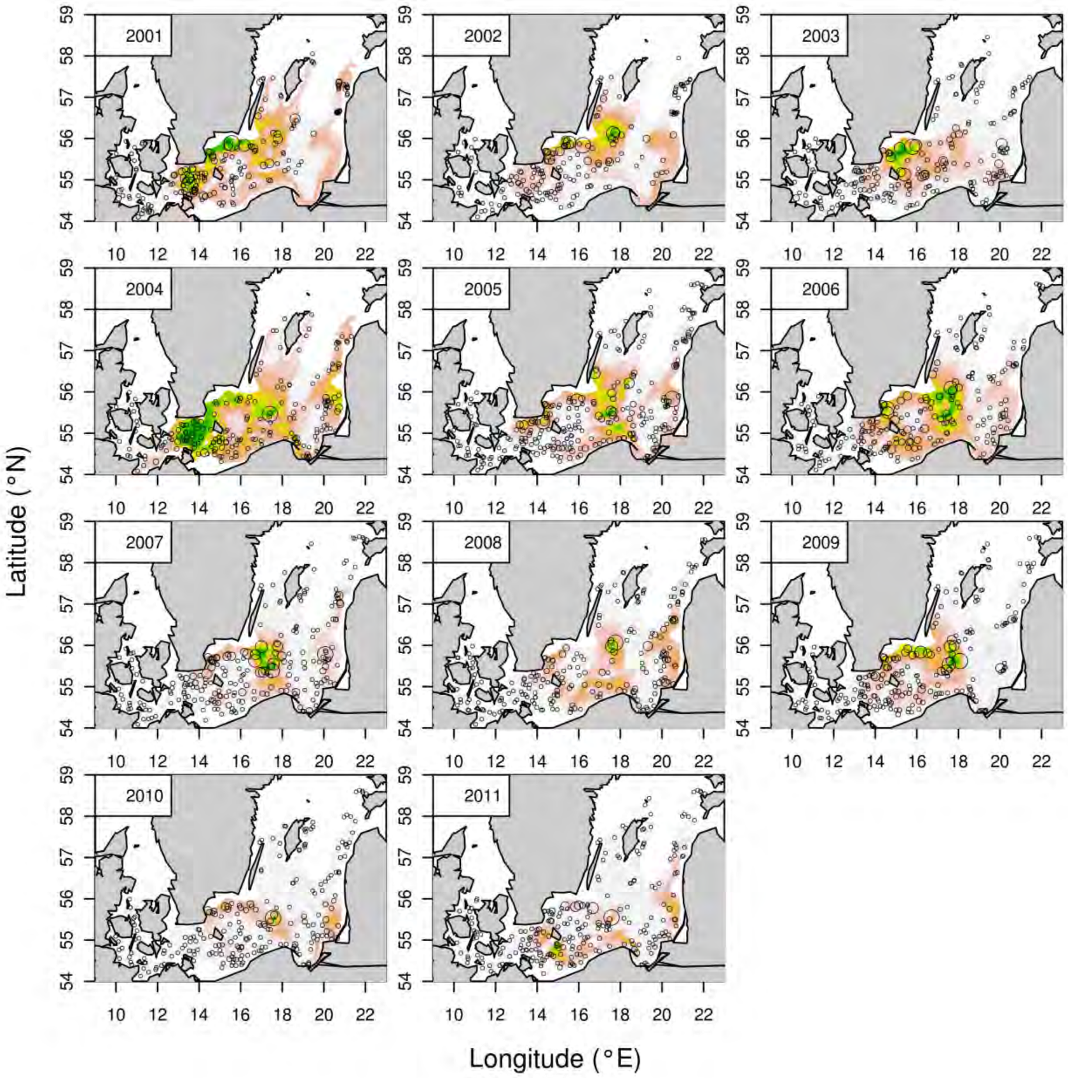

Figure 2. Distributions of discard sensitive size classes of cod (30-37cm) in the Baltic Sea during quarter 4 (October to November) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

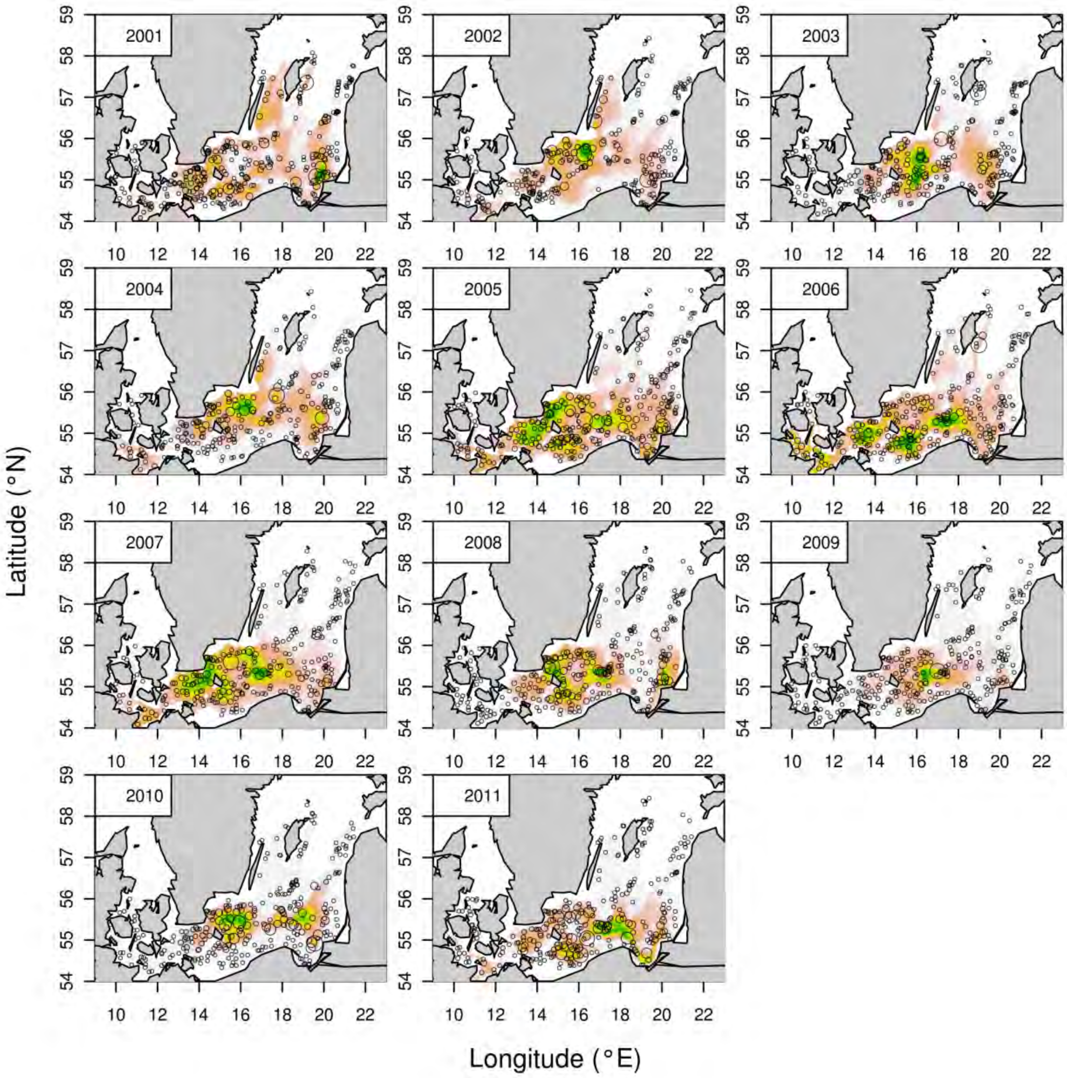

Figure 3. Distributions of the smaller commercial size classes of cod (38-48cm) in the Baltic Sea quarter 1 (February to March) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

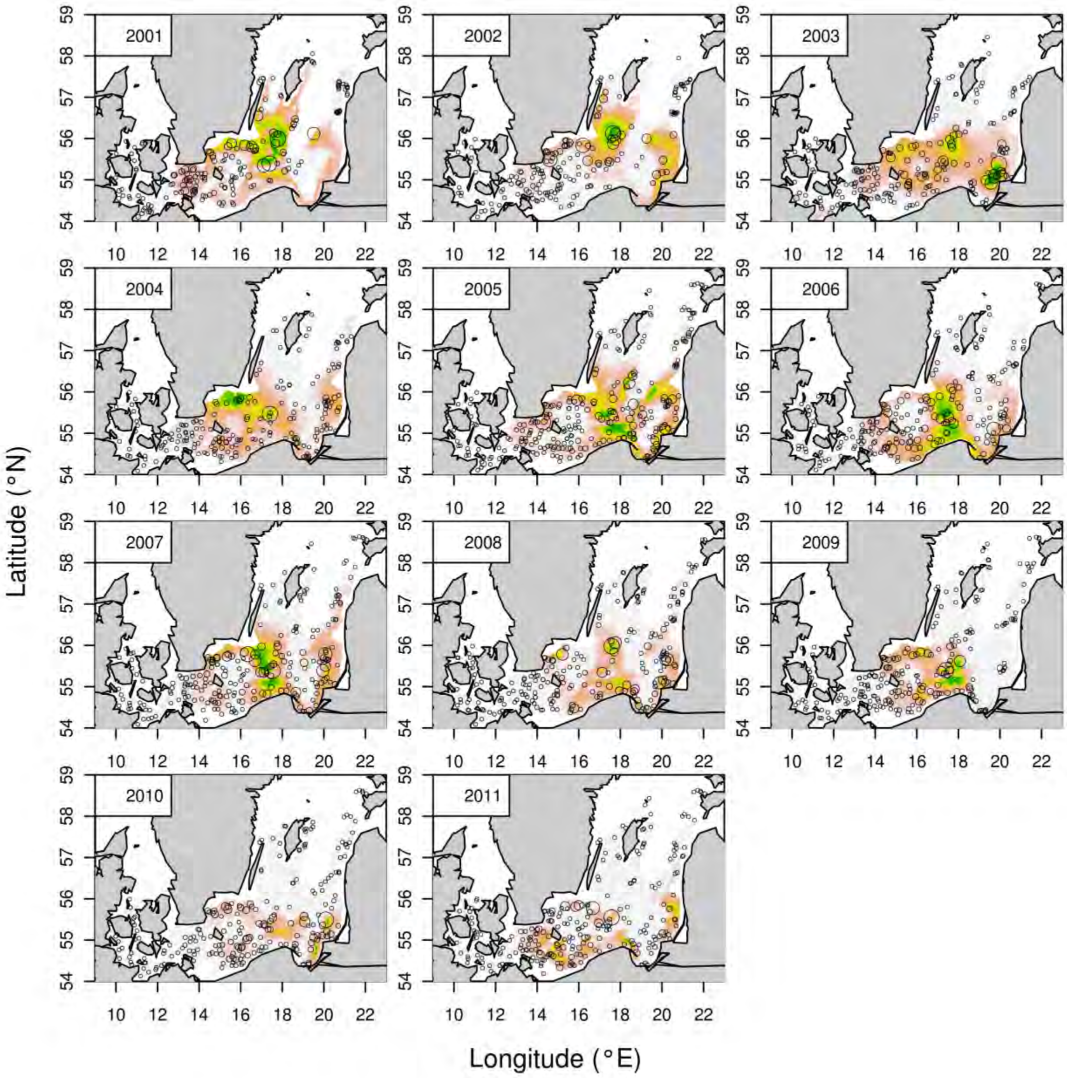

Figure 4. Distributions of the smaller commercial size classes of cod (38-48cm) in the Baltic Sea during quarter 4 (October to November) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

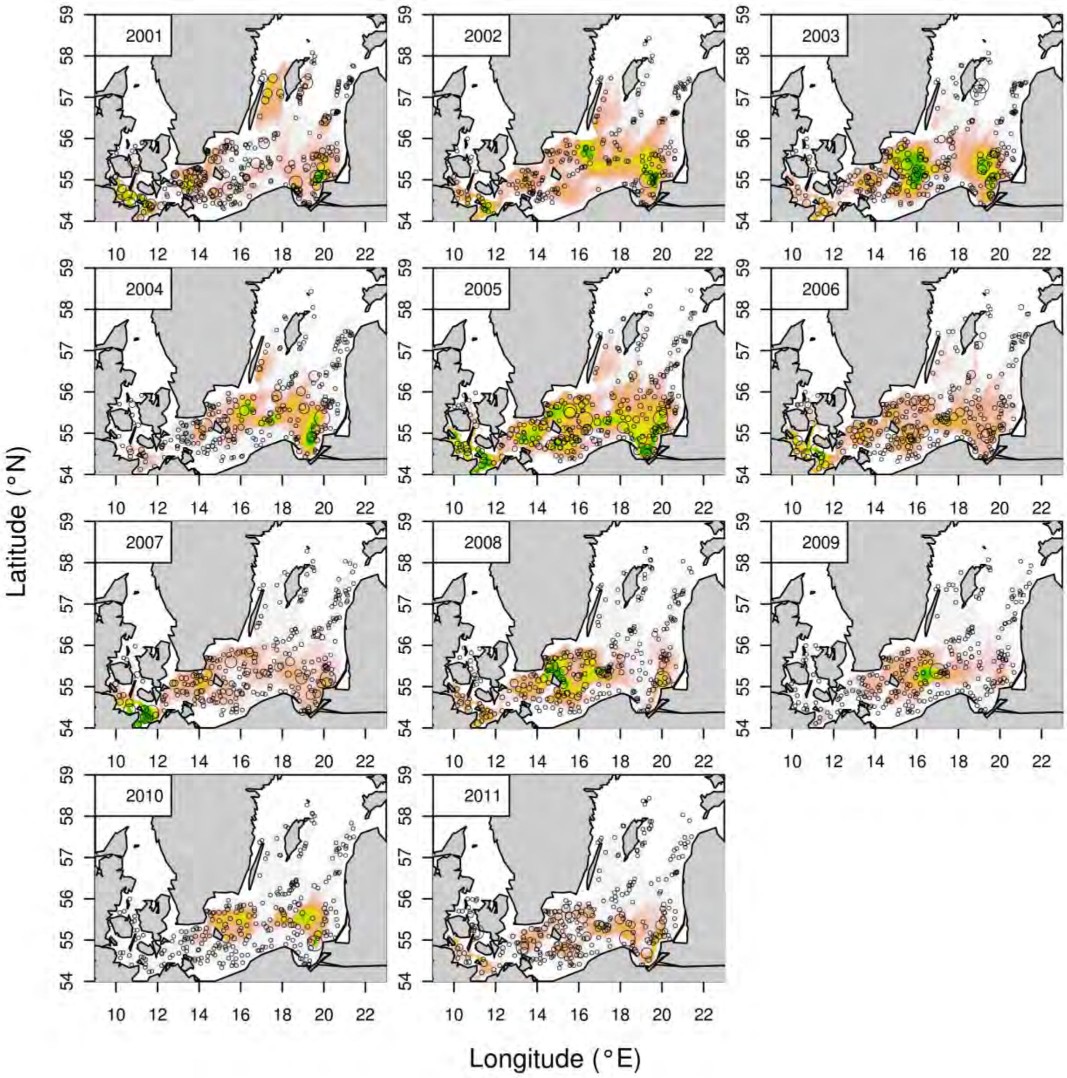

Figure 5. Distributions of the larger commercial size classes of cod (>48cm) in the Baltic Sea during quarter 1 (February to March) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

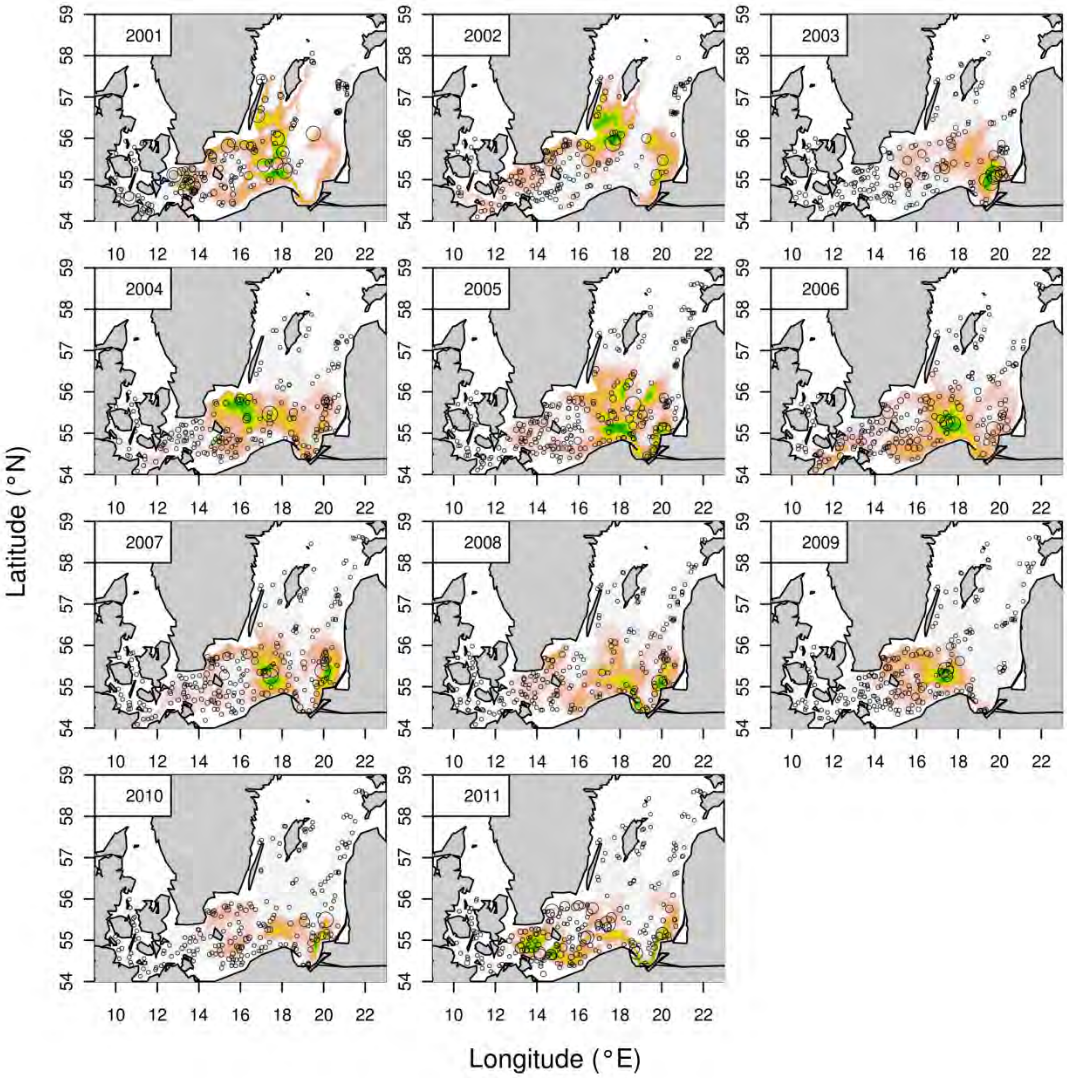

Figure 6. Distributions of the larger commercial size classes of cod (>48cm) in the Baltic Sea during quarter 4 (October to November) as estimated by BITS trawl surveys in 2001-2011. The bubble size is proportional to the observed catches in the BITS data set.

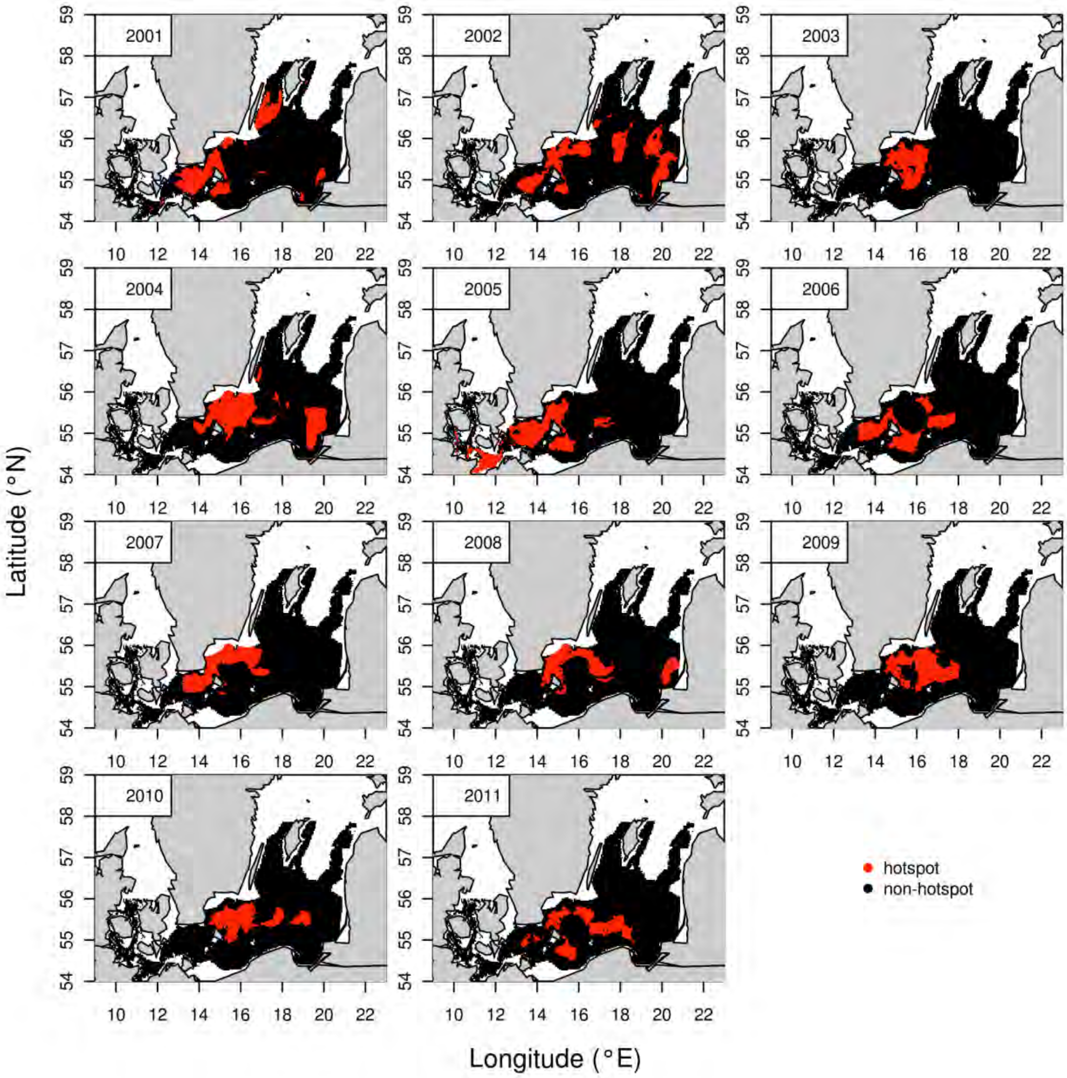

Figure 7. Hotspots of discard sensitive cod (30-37cm) during quarter 1 (February to March) between 2001 and 2011 in the Baltic Sea as estimated by BITS trawl surveys. A hotspot is defined as the minimum area covering 50% (25 and 75% are not shown) of the total distribution of discard sensitive size classes of cod (30-37cm).

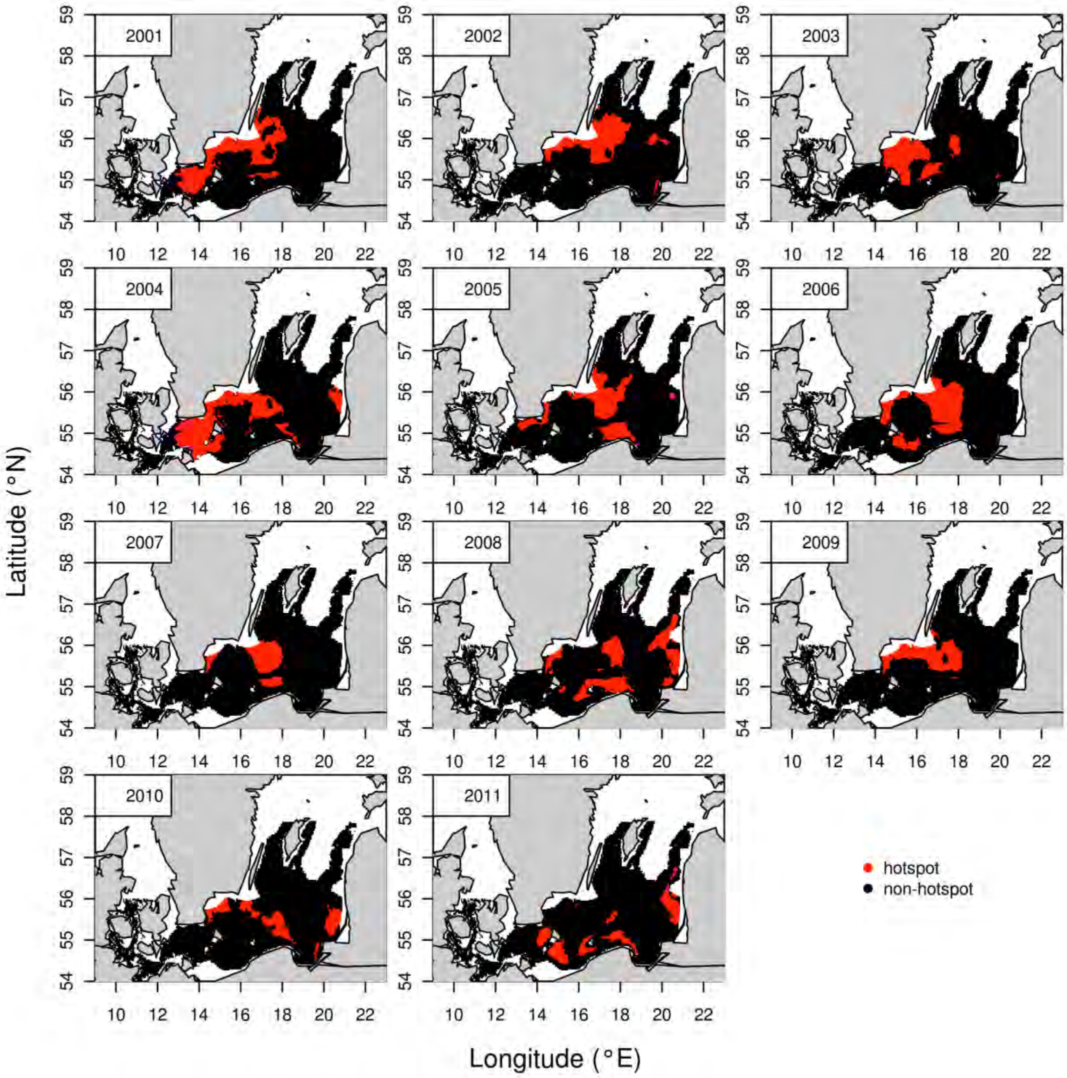

Figure 8. Hotspots of discard sensitive cod (30-37cm) during quarter 4 (October to November) between 2001 and 2011 in the Baltic Sea as estimated by BITS trawl surveys. A hotspot is defined as the minimum area covering 50% (25 and 75% are not showed but they are available under request) of the total distributions of discard sensitive size classes of cod (30-37cm).

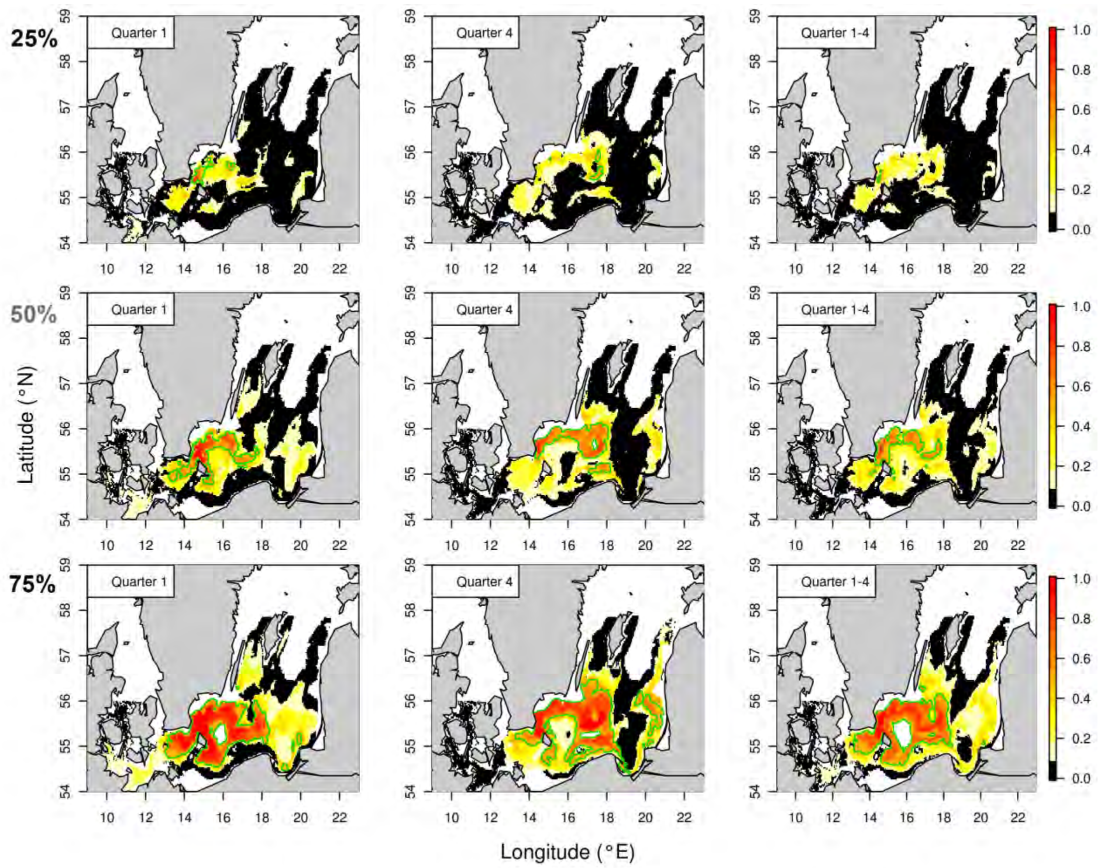

Figure 9. Persistence hotspots of discard sensitive size classes of cod (30-37cm) between 2001 and 2011, in the Baltic Sea, quarter 1, 4 and combined for respectively conservation goals of 25, 50 and 75%. Scale range from 0 (cells never selected as hotspot) to 1 (cells always selected as hotspot). The green polygon outline the areas defined as hotspot more than 50% of the time between 2001 and 2011.

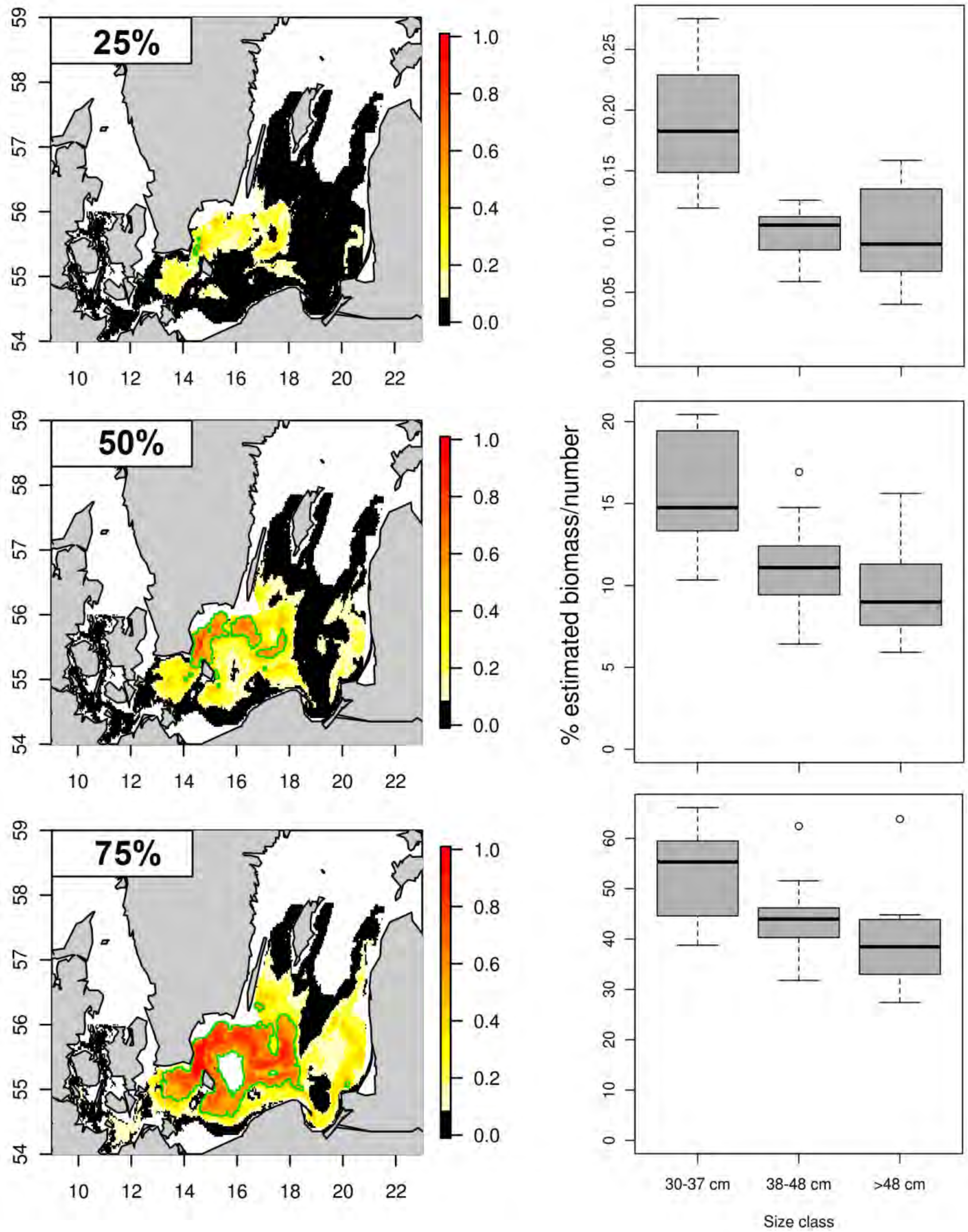

Figure 10. Overlay analysis of the combined persistence hotspot area for quarter 1 and 4 combined on all size classes of cod (30-37, 38-48 and 48cm) for respectively conservation goals of 25, 50 and 75% (green polygons from Fig. 9). The box plots shows the estimated fraction in numbers or biomass within the potential closures (green polygons) over time of cod in each size class (30-37, 38-48 and >48cm) of the total estimated distribution. Boxplot indicates median, 25th and 75th percentiles, minimum and maximum values, and outliers.

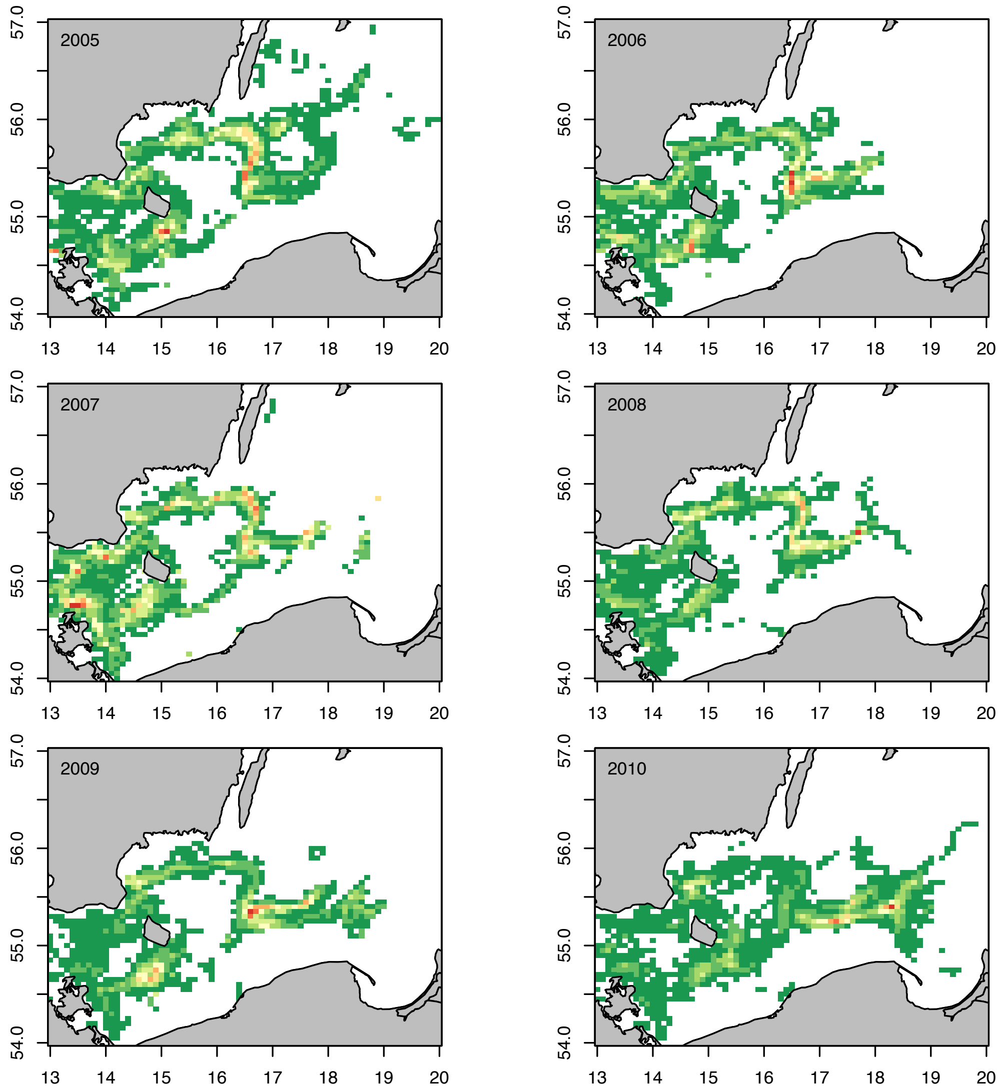

Figure 11 Distributions of total landings of cod in the Baltic Sea. Relative colour scale within year green to red indicates increased landings.

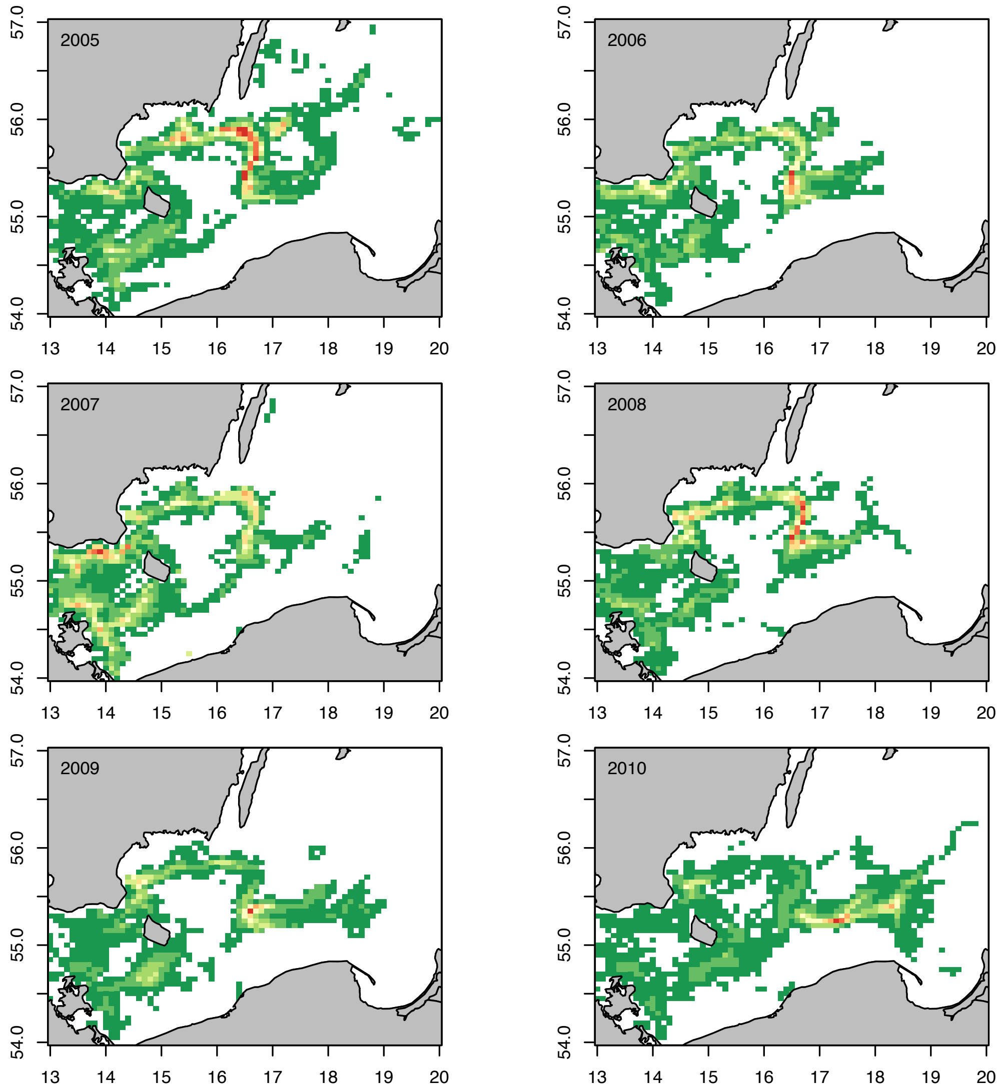

Figure 12 Distributions of total effort of cod trawl fishery (vessels ≥15m) in the Baltic Sea. Relative colour scale within year green to red indicates increased landings.

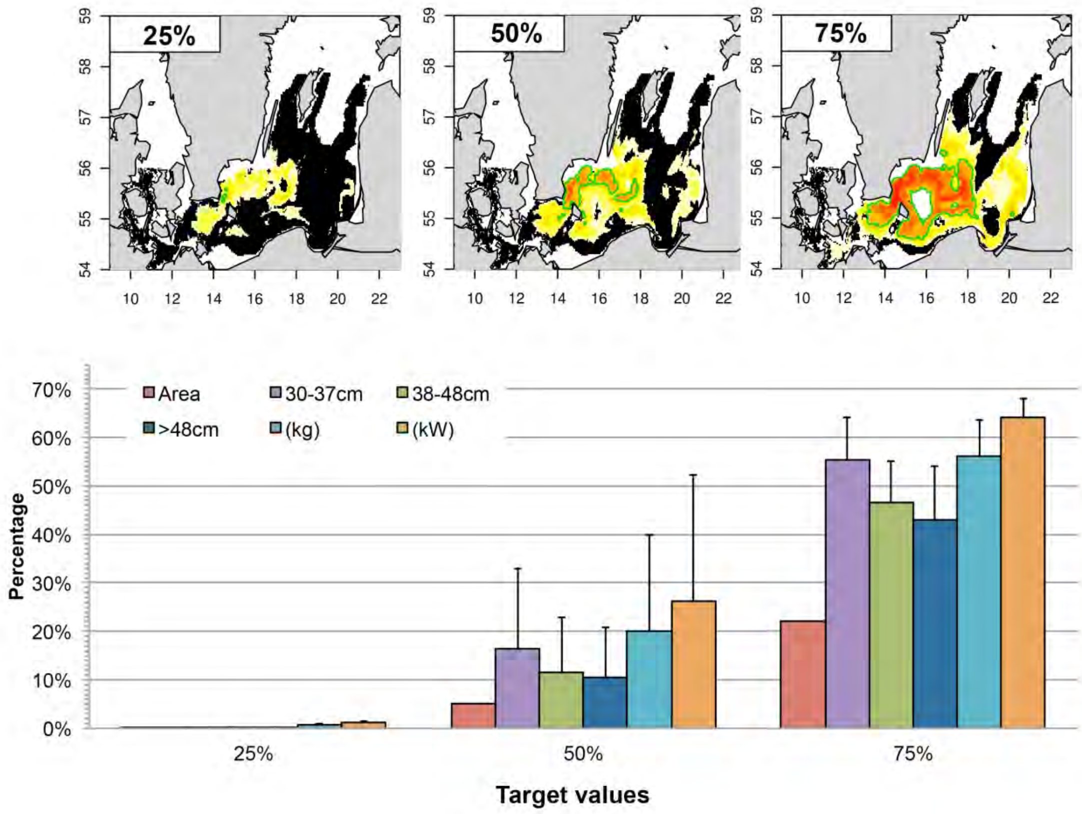

Figure 13. Overlay analyse of the different size classes of cod (30-37, 38-47 and >48cm) and the fishery (landings [kg] and effort [kW]) in the suggested closed area between 2005 and 2010. Maps are showing the results of the combined persistence analysis of quarter 1 and 4 combined, with the green polygons outlining areas potentially candidate for closure. The diagram is showing the relative size of the closed area, the average fraction over time of cod in each size class (30-37, 38-48 and >48cm) and fishery (mean landings [kg] and effort[kW]) of the total estimated distribution between 2005 and 2010, and standard deviation.

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Annex 3:
Impact study of technical measures in the Swedish Baltic Sea cod fishery

Impact study of technical measures in the Swedish Baltic Sea cod fishery

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Introduction

Discarding is the practice of returning unwanted catches to the sea. In the EC, the discarded (and often dead) fish and shellfish do not have to be counted against quotas. However, the new proposal for a reformed common fisheries policy (CFP) foresees provisions to end this practice (EC 10629/13 PECHE 245 CODEC 1359). In the Baltic it is suggested that the discard ban should start in 2015 for the demersal fleet, which will result in all catches having to be counted against quotas. In the Baltic, discards of cod are mostly an effect of the mismatch between the gears' mesh sizes, the minimum landing size (MLS) and the stock's size distribution (Suuronen et al. 2007). Even though the discard rates in the Baltic are considered relatively low compared to other areas, the latest trend is that discard rates are increasing and were calculated as much as 25% in 2012 (ICES/WGBFAS 2013). The new CFP also suggests that the MLS for commercial fish shall be eliminated and minimum conservation reference sizes (MCRS) should be used instead. The MCRS means the size for a given species below which the sale of catches shall be restricted to reduction to fish meal, pet food or other non-human consumption products only which will result in much lower market prizes.

The reasons for discards are many and include unwanted species (i.e. species that are not the target for the particular fishing operation), wrong size (under MLS or too low a market price), quotas reached, fish are of poor quality (caused by gear or predation in nets or mis-handling etc.), or high grading (certain attributes of a fish make it more marketable and therefore more valuable than another and the less valuable is discarded - this is often related to size). Furthermore, the management system at hand might affect discard rates, where e.g. Branch et. al. (2006) found Individual Transferable Quotas (ITQs) to reduce discards in British Columbian groundfish fishery. However, there are many factors within a management system that can affect the rate of discarding fish and Catchpole et. al. (2006) identified six causes for discards in the English fishery for Nephrops; Gear selectivity, environmental variables, quota restrictions, MLS, market forces, and industry resistance to management measures. They found poor gear selectivity to be the main direct cause of discarding, and low incentives to use selective gear as a major obstacle to discard reductions.

The implementation of a discard ban may have a short run negative impact on the profitability and e.g. Catchpole et al (2005) find resistance from the industry to implement discard reductions due to expected economic losses. Different types of measures could be proposed in order to reduce the negative impact of the foreseen discards ban on the fishing industry and at the same time allow reliable biological information for stock assessment.

In this report we analyse and discuss the effect of four different factors (gear selectivity, minimum landing size, a discard ban, and the size distribution of cod in the stock) affecting discards and we present both a short-term analysis, where we analyse the economic effects of these factors, and a biological medium-term forecast where the effects on stock development is taken into account. The short-term analysis is performed by applying the selectivity of the five different codend types tested in the commercial vessel sea trial (Bacoma 120/105 (Ref), Bacoma 120/105 with grid, T90-8mm single thread 120, Bacoma 120/130, and Full square mesh codend 120) to different levels of MLS (or MCRS), different size distributions of cod during the last 20 years (tree periods), and whether a discard ban is imposed or not. For each scenario, the economic outcome of catching the individual quota for a standard vessel (trawler 18-24 meters) in the Swedish Baltic Sea fishery is calculated. This enables an economic comparison between different codend types and different management measures in order to increase the legitimacy of proposed types within the industry. In the medium-term forecast the theoretical effect between the Bacoma 120/105 (Ref) and the Bacoma 120/130 codend on the catches and on the spawning biomass (SSB) of Eastern Baltic cod is estimated.

Material and Methods

Short-term analysis

In the short-term analysis, no stock effects are considered and thus all effects are based on the costs and revenues for fishing a pre-determined quota in one year.

Factors affecting the economic performance for a Swedish standard vessel

The economical outcome of a fishery is directly dependent on quota, stock size and size distribution of target species, and technical measures. We build the scenarios based on the following main factors:

- Gear selectivity
- Minimum Landing Size
- Discard ban
- Size distribution of cod in the stock

Gear selectivity (retention likelihood)

Most of the size selectivity is known to take place in the rearmost part of the trawl - the codend. In a commercial vessel sea trial we tested 4 codends against a reference codend (Bacoma 120/105, 120 mm Bacoma window and 105 mm diamond mesh in the lower panel). The size selectivity of a gear could be expressed as the retention likelihood. Retention likelihood describes the probability for each size classes to be retained in the codend. Codends retention likelihood was calculated against the reference trawl in the commercial vessel sea trial (for details see Annex 5: Commercial Vessel Sea Trial, Figure 1).

Gear retention likelihood scenarios:

- Bacoma 120mm/105mm (Reference codend)
- Grid system with a standard Bacoma 120mm/105mm codend
- T90-8mm single thread (120mm)
- Bacoma 120mm/130mm
- Full square mesh codend (120mm)

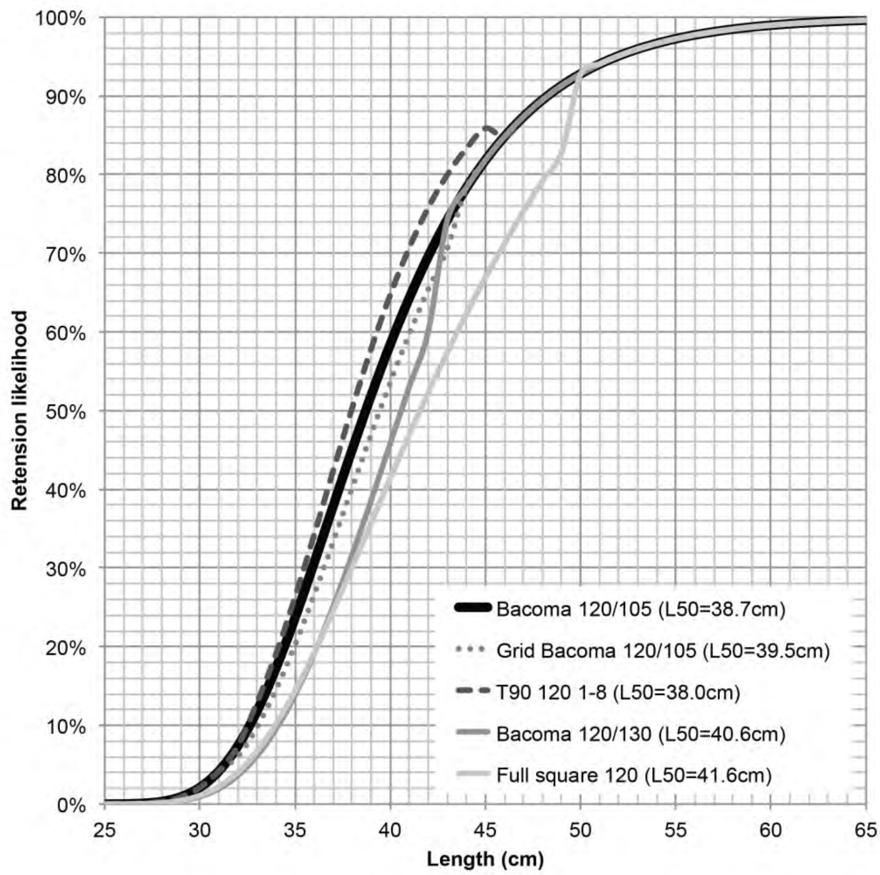

Figure 1. Retention likelihood of the reference codend Bacoma 120/105 and the codends tested in the commercial vessel sea trial (for details see Annex 5: Commercial Vessel Sea Trial). The L50 value is the length of cod where half of the individuals (50%) are retained in the trawl and half of the individuals go through the trawl and is lost.

Minimum landing size (MLS)

In the Baltic cod fishery, the current minimum landing size (MLS) is 38 cm. This was increased in 2003 from 35 cm and before that from 33cm in 1995 (Suuronen et. al 2007). In the North Sea including Skagerrak and Kattegat the MLS for cod is 35cm. The rational for including MLS 35cm as a factor is the current debate of a preferred MLS in the Baltic cod fishery.

Minimum landing size scenarios:

- 35cm
- 38cm

In the scenarios with a discard ban, some of the landed fish will be below MLS and these landings are supposed to be subtracted from the quota, but will not generate any revenues in contrast to the CFP proposal which states that the fish under a MCRS shall be restricted to non-human consumption with much lower market prizes.

Discard ban

A major change in the new common fishery policy (CFP) is the introduction of a discard ban, which will be introduced in the Baltic cod fishery 2015 (EC 10629/13 PECHE 245 CODEC 1359). We analyse the economic impact of introducing a discard ban in the Swedish Baltic Sea cod fishery under the assumption that the ban is fully enforceable. The rationale behind this is that camera surveillance on each vessel is proposed by the Swedish Agency for Marine and Water Management (2013), the agency responsible for fisheries control. In this study we have set the catch quota equal to the landing quota before the discard ban. Giving the same total landing, but divided in marketable catch (>MLS) and not marketable catch (<MLS).

Discard ban scenarios:

- no Discard ban (landing quota)
- Discard ban (catch quota)

Size distribution of cod in the Eastern and Western Baltic

Data on spatial and temporal distribution of all size classes of cod were collated from the Baltic international trawl survey (BITS), extracted from ICES-DATRAS database for the period 1991 to 2013. Raw data on abundances from BITS surveys on length distribution were standardised using conversion factors for respectively length class and gear used in respectively survey (Baltic International Fish Survey WG 26-30 March, 2007). Stock dependent length-weight relationships were used to calculate biomasses. Averaged length distribution was calculated for the three periods 1991-2000, 2001-2010 and 2011-2013 (quarter 1) for each ICES subdivision SD24 and SD25 (Figure 2).

Size distribution scenarios:

- 1991-2000 (1990s)
- 2001-2010 (2000s)
- 2011-2013 (Q1) (2010s)

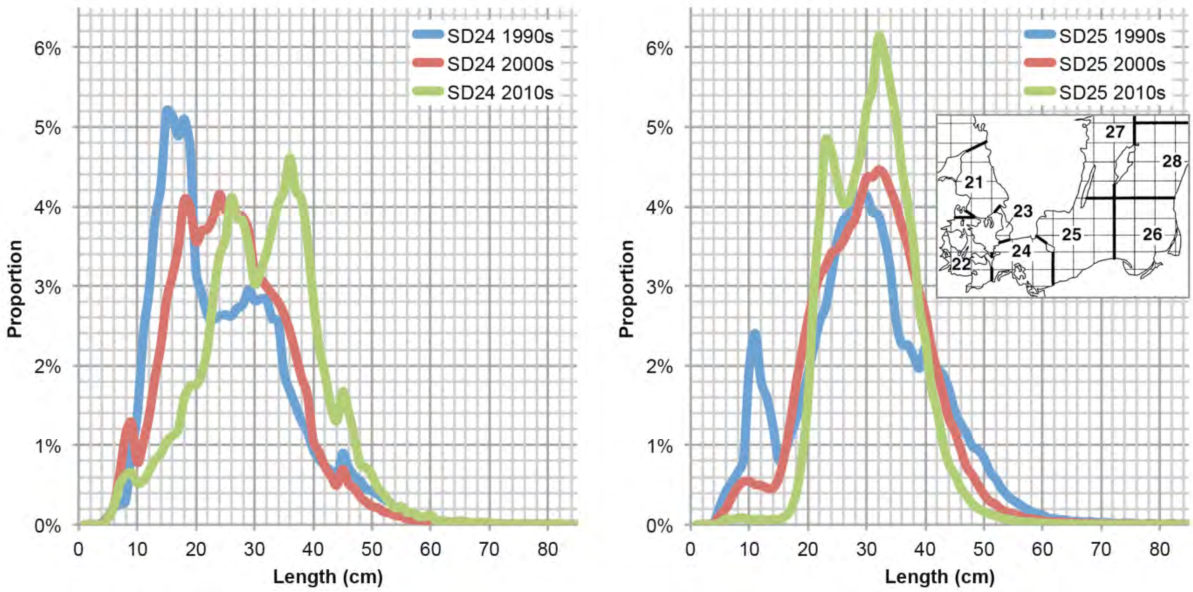

Figure 2. Average size distribution of cod in number in ICES subdivision SD24 and SD 25 between 1991-2000, 2001-2010 and 2011-2013 collected in Baltic international trawl survey. Map showing ICES subdivision in the south of Baltic.

Economic Method

Catch composition

Catch compositions for a standard Swedish trawler and in the different scenarios were calculated by multiplying the relative number of individuals in each size class in respective stock (Figure 2) with the retention likelihood for each size class (Figure 1). This was done for each stock and size distribution (SD24 size from 1990s, SD24 2000s, SD 24 2010s, SD25 1990s, SD25 2000s and SD25 2010s), and each suggested codend (Bacoma 120/105 and T90 1-8, Bacoma 120/130, Full squared 120 and Grid with Bacoma 120/105). This procedure generates the number of individuals retained in the trawl and lost (cod not selected by the specific mesh) in each size class in each combination of size distribution and stock. Both the number of retained and lost individuals was then divided into individual below MLS and into the 5 EU commercial size-categories above MLS (38-48, 49-62, 63-79, 80-95 and >96cm) and multiplied with the mean weight for each size class and stock. The total weight of both lost and retained individuals in the different trawl types gives the total amount of cod (kg) passing through the trawl (PTT) needed to catch a certain amount of fish. For each scenario the total weight of retained individuals above respective MLS (35 and 38cm) was then normalized to a given stock size. The total catch in a scenario is

$$Catch_k = PTT_k * RL_k$$

Where *k* is the size-class (cm length of the fish), $Catch_k$ is the catch in each size-class, PTT_k is the amount of fish passing through the trawl in each size-class, and RL_k is the retention likelihood. In the scenarios we assume historically observed size distributions within the stock, which refers to the size class of the cod and not to the size of the total biomass.

The catch composition is converted to landing categories (L) such that each landing category corresponds to a specific landing price fitting the EU commercial size-categories.

$$L_i = \sum_{k=xi,lower}^{xi,upper} Catch_k$$

Where L_i is the landed volume in size category *i*, $x_{i,lower}$ is the lower boundary (in cm) for size category *i*, and $x_{i,upper}$ is the upper boundary for size category *i*. Without a discard ban $X_{i,\,lower}$ will be 35 for MLS35 and 38 for MLS38 for the smallest size category. With a discard ban it will be zero since all catches will be landed.

Revenues and Costs

The Swedish cod quota is allocated to individual fishermen on a yearly basis, and the management could be described as an individual non-transferable quota system. The yearly quota allocations used in the model is for vessels less than 161 BT corresponding to the size category used for cost calculations. The quota is split between SD24 and SD25, where the latter is the most important area in terms of catch possibilities. The two stocks have different fish abundance and size distributions, which implies that the catch rate per hour and the amount of fish passing the trawl per hour differs.

The economic analysis is based on a model calculating the revenues and costs for a vessel fishing its yearly catch quota in both SD24 and SD25, in each of the different scenarios. Revenues are calculated as

$$Revenue = \sum_{i=1}^{I} p_i * L_i$$

where p_i is the price in each size-class.

Costs are calculated for each scenario as

$$Total\ cost_S = C_{DAS} * DAS_S$$

where *s* represents a scenario. Total cost is the days at sea necessary to catch the quota (DAS_S) times the cost of operating a vessel one day (C_{DAS}) . The time necessary for catching the quota will differ between scenarios since the trawling efficiency will differ depending on gear design and stock composition. The time necessary to catch the quota is for each scenario defined as:

$$DAS_s = (Q * NPTT_s)/PTT_{DAS}$$

Where *Q* is the vessel quota, $NPTT_s$ is the amount of cod necessary to pass through the trawl in scenario *s* in order to catch one kilo of fish, and PTT_{DAS} is the amount of cod passing through the trawl in one day of fishing. The total landings, including undersized fish in the case of a discard ban, will always equal the quota:

$$\sum_{i=1}^{I} L_i = Q$$

It is assumed in the model that the quota is always caught, which is a realistic assumption as long as the fishery is profitable.

Economic Data

Landed volume for each EU size category of fish is calculated as the share of landed fish in the size-class in the relevant scenario multiplied with total quota (Table 1). The price for each size-class is calculated from landing declarations in 2010 for Swedish landings of cod in Baltic Sea harbours. The operating costs are based on economic data collected with EU's Data Collection Framework (DCF). The costs are defined as fuel costs, repair costs, other variable costs and fixed costs that are not due to capital investments (e.g. harbour fees). All costs are based on trawlers between 18 and 24 meters primarily fishing for cod in the Baltic Sea and considered "a standard vessel" in the Swedish trawl fishery for cod in the Baltic Sea in this analysis. The difference between landing value and operating costs is the gross value added (GVA) as defined in the DCF, and this is used as indicator in of the economic performance in the analysis. We do not take fixed costs into account since the vessels are assumed to be identical. The GVA shall cover capital costs, labour costs and profit for the industry.

The amount of cod passing the trawl in one DAS (PTT_{DAS}) , i.e. both retained and lost fish, is calculated based on the amount passing the reference trawl in order to catch 1 kilo of fish and known catches per hour and hours fishing per day such that PTT_{DAS} = Observed catch per hour *hour trawled per DAS*cod passing the trawl per kg. Catch per hour and hours trawled per DAS are calculated for vessels 18-24 meters using data extracted from on-board data from the Swedish sea sampling program (DCF).

Table 1. Data for calculation of economic performance Price refers to the EU commercial size category.

Data input	SD24	SD25
Price, small (€/kg), EU size 5, 2010	1,23	1,23
Price, medium (€/kg), EU size 4, 2010	1,56	1,56
Price, large (€/kg), EU sizes 1-3, 2010	1,71	1,71
Cost per DAS (€)	2 121	2 121
Catch rate per hour (kg), mean 2000-2012	236	306
Pass trawl per hour (kg)	637	1032
Trawl hours per day	12	12
Pass through trawl per day (kg), PTT_{DAS}	7 640	12 387
Vessel quota (kg)	47 520	376 200

Medium-term forecast

The medium-term forecast focus on biological consequences of gear selectivity taking the dynamic effects of selectivity into account on the stock development. We used the input and output data from the latest assessment (WGBFAS 2013) to run a forward stock projection with the status quo selection, i.e. Bacoma 120/105 (Ref), and then we compare it to a similar forward projection but assuming a selection curve (retention likelihood) based on the Bacom120/130 codend.

The shift from a Bacoma 120/105 (Ref) to a Bacoma 120/130 codend will in theory only affect cod sizes between 30 and 42 cm. This shift in selection pattern was used to calculate the theoretical retained length classes of cod with the Bacoma 120/130 codend. Successively, we applied this selection on the length frequency distributions of cod caught by the Swedish trawl fisheries in 2013 (Data collection framework, DCF, 2013) (weight and catch numbers at age) and we assumed that the Swedish trawl fleet took the entire catch (TAC based on F=0.3) when projecting the stock forward. The constant fishing mortality will in turn result in different TAC in the forecast. The reason for using data from 2013, and projecting it forward from 2012, was due to the fact of the negative trend in weight at age the resent years. The Bacoma 120/130 codend will affect catch at age both in numbers and in weight. The new weights at age were recalculated using an age-length-key based on Swedish data (2012, DCF) only assuming that the catch at age changed accordingly to a size selection curve based on a Bacoma 120/130 codend, i.e. weights at age were slightly higher compared the weights at age used in the status quo assessment. The catch numbers at age of the last year was recalculated in the same way as for the weight at age, i.e. resulting in fewer cod caught at age 2, 3 and 4 but with the same numbers for older ages. One problem when using the Swedish age-length-key in combination with the selection curve based on a Bacoma 120/130 codend was that it did not include the whole size spectra (30-42 cm) but only 35-42 cm individuals. This means that the forward projection will slightly underestimate the effect of the Bacoma 120/130 codend both in terms of stock development and catch. Maturity at age was kept as the average of the last 3 years (2010-2012) in both simulations.

The forecast was based on the FLR routine and it simulated the stock and the catches forward in time starting from the estimates obtained at the 2013 stock assessment (WGBFAS 2013). The Bacoma 120/130 codend size selection was assumed to start in 2012 i.e. terminal year. The forward simulations was based on: F(2012) = Fsq = 0.37 (F_{bar} ages 4–6, mean of the last 3 years, scaled to F2012), F (2013-2017) = F_{mp} = 0.3 and recruitment equal to 128 900 millions (geometric mean of the 15 years; 1998-2012) or as estimated by a Beverton & Holt stock and recruitment curve based on the whole time series (1966-2012). For the latter, uncertainties on recruitment was simulated as resampled (i.e. 500 iterations) from the residuals of the fitted Beverton & Holt stock and recruitment curve. The forecast was run to 2030 but as the development in the Eastern Baltic cod stock is uncertain we chose to only present data to 2017 i.e. when results suggest a difference between scenarios.

Results

Short-term economic consequences

Since focus is on the relative performance under different policy scenarios, the results are expressed in relative terms using the Bacoma 120/105 (Ref) trawl, MLS35 and no discard ban as baseline with reference value of 1 which all other scenarios are compared to (Table 2). This corresponds to a gross value added of €264 thousand for a standard vessel. The outcome varies with a factor of 2.7 between 164 k€ to 446€ depending on the combination of stock composition and management regulations. Observe that this is short-term results, i.e. no stock development effects are considered.

Table 2. Relative economic performance compared to the present situation with no discard ban, MLS 38cm and Bacoma 120/105 (Ref), in the Swedish Baltic cod trawl fishery.

Size distribution	Discard ban	No		Yes	
	Gear/MLS	35cm	38cm	35cm	38cm
1990s	Bacoma 120/105 (Ref)	1.68	1.66	1.64	1.54
	Bacoma 120/130	1.66	1.65	1.64	1.57
	Full square 120	1.63	1.62	1.61	1.54
	Grid Bacoma 120/105	1.67	1.66	1.63	1.55
	T90 120 1-8	1.69	1.67	1.64	1.54
2000s	Bacoma 120/105 (Ref)	1.43	1.36	1.37	1.17
	Bacoma 120/130	1.37	1.32	1.33	1.19
	Full square 120	1.31	1.25	1.27	1.12
	Grid Bacoma 120/105	1.41	1.35	1.35	1.17
	T90 120 1-8	1.46	1.39	1.39	1.18
2010s	Bacoma 120/105 (Ref)	1.17	**1**	1.09	0.77
	Bacoma 120/130	1.03	0.89	0.99	0.74
	Full square 120	0.94	0.76	0.89	0.62
	Grid Bacoma 120/105	1.12	0.96	1.05	0.75
	T90 120 1-8	1.23	1.06	1.14	0.80

The economic performance is highest irrespective of trawl design for the size distribution represented by 1990s stock, followed by 2000s and 2010s. Managing the fishery with MLS 35cm generates higher economic performance than MLS 38cm, and the economic performance is higher without a discard ban than with a ban.

Figure 3 shows the interaction between a discard ban and MLS as an average, over all stock size class distributions (1990s, 2000s, 2010s) and gear types (codends). The economic performance is dependent on both the MLS and of a discard ban, where the discard ban decreases vessel performance and a MLS 35cm increases performance compared to MLS 38cm. On average, a discard ban will reduce the economic performance for a vessel with 8% taking into account that no change of the quota is made. The negative effect of a discard ban on a vessel's performance increases to about 15% if we only consider the last suggested size class distribution (2010s), still assuming the same quota, which is a result of a higher discard rate in this scenario and even worse (23%) compared to if we in addition to the 2010s size distribution assume an MLS of 38cm.

A MLS at 35cm will increase the economic performance with on average 11% and eradicate the negative effect of a discard ban on vessels economic performance (Figure 3), assuming constant prices for the smallest size category. However, landings of smaller individuals could negatively affect the prizing of the smallest marketable size category (see 7 Sensitive analysis)

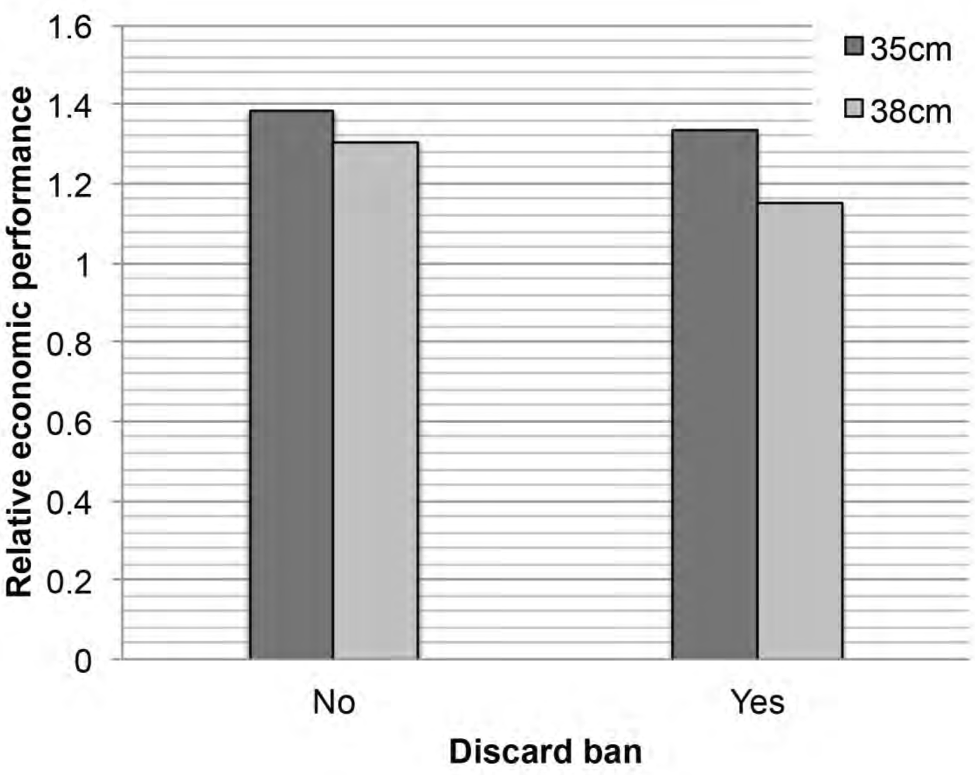

Figure 3. The effect of a discard ban and different MLS on the economic performance of a standard vessel.

The effect of size class distribution (per time period) and gear selectivity on the economic performance, suggests that the effect of gear selectivity on economic performance is dependent of the size structure on the stock (Figure 4). In the 1990s, the effect of the different gear selectivity on the economic performance, have only a minor effect with a maximum of 2% of the outcome between the most selective gear (Full square 120) and the less selective gear (T90 120), and even less if we take into account a discard ban (Table 2). On the other hand, taking into account at the latest size class distribution (2010s), the economic performance varies up to 31% between different gear types. This means that the effect, in terms of short-term economic loss of an introduction of more selective gear, is more pronounced at present situation when smaller size classes dominate the size distribution.

Figure 4. The interaction between size class distribution and gear selectivity on vessels economic performance as an average over all MLS and discard options.

Sensitivity analysis

Two sensitivity analyses were performed to check the robustness of the results; one economic and one on with biologic uncertainty. The economic uncertainty stems from the landing price of cod. In the baseline calculations the 2010 price level is assumed. However, the relative performance of different gear types might be sensitive to changes in the relative prices between landed size categories. The development of the prices from 1997 to 2011 is presented in figure 5, for Swedish landings of cod in Baltic Sea harbours.

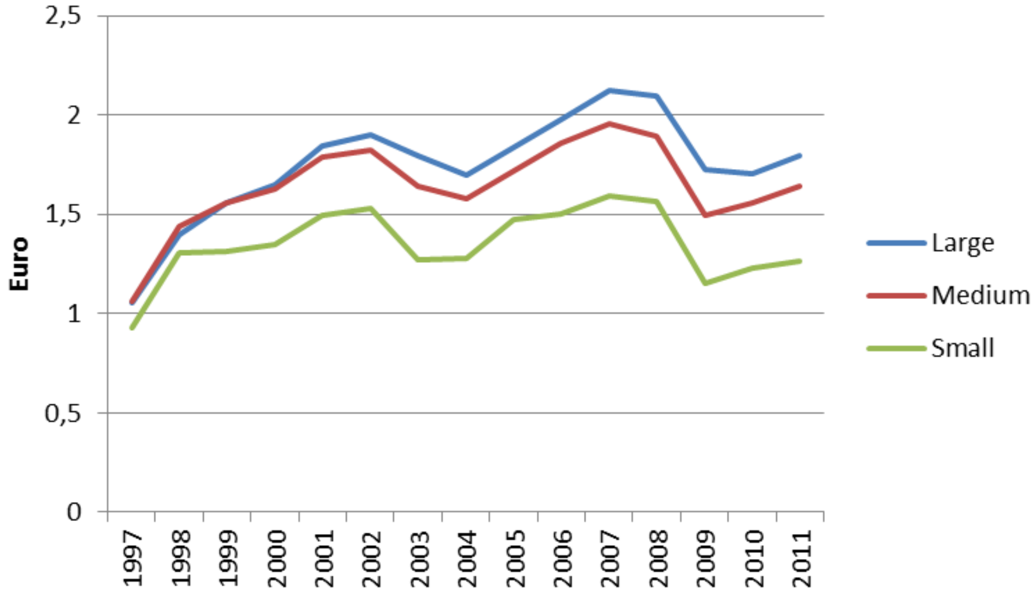

Figure 5. Price development 1997-2011 for cod landed in Swedish Baltic Sea harbours, (SEK)

On average, the price difference between size categories has been somewhat smaller during the period than was the case in 2010 and we used the average values for the sensitivity analysis: Small € 1.17, medium €1.56, and Large € 1.71. The second price alternative is a reduction of the price of small cod with 5 % for the case of MLS 35cm. A decrease in prices for small cod could be expected since the average size of the cod becomes smaller at the same time as the supply of small cod increases. The price change, due to increased supply, is expected to be small (Kristofersson and Rickertsen, 2004) so the main effect should be from smaller sized specimens above MLS.

The interaction between MLS and discard ban for the three price alternatives are presented in figure 6 where “1997-2011” is the average price alternative and “Small cod” is the 5 % reduction in price for small cod.

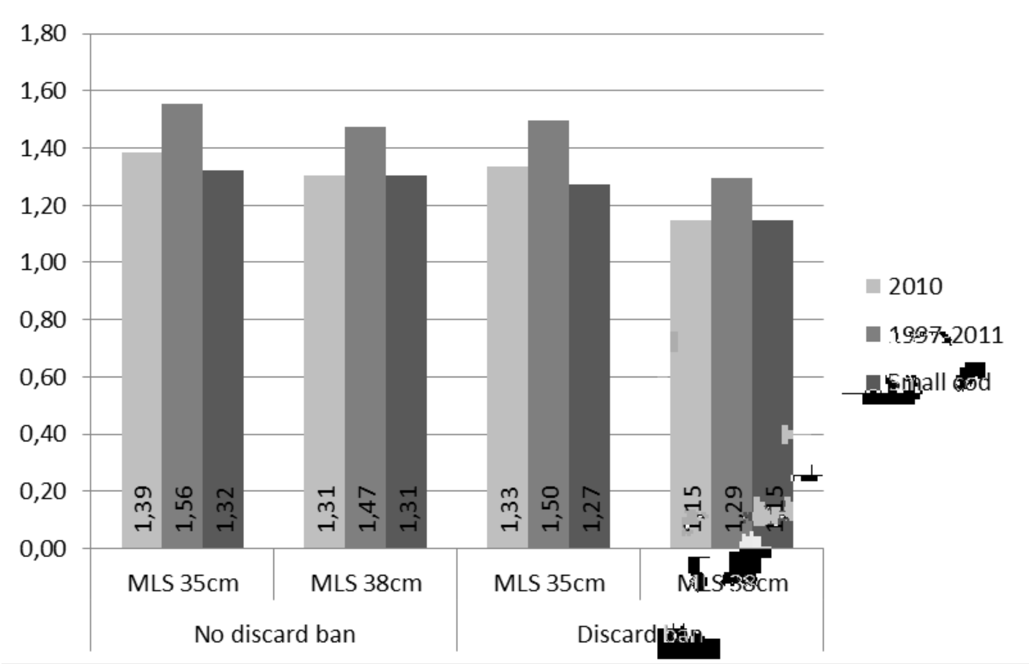

Figure 6. Sensitivity analysis. MLS and discard ban.

The analysis suggests that it is possible to keep the profitability in the sector when imposing a discard ban if the MLS is reduced to 35 cm for both the baseline scenario and the “1997-2011” price scenario. However, if the price of small cod decreases the additional income from landing small cod in the MLS 35cm case, compared to MLS 38cm does not compensate for the reduced revenues caused by the discard ban. Thus, the possibility to compensate the fishery economically by reducing MLS is dependent on stable prices.

In the second sensitivity analysis, the amount of fish passing through the trawl per fishing day is increased and decreased with 25 % (Table 3). This will capture the results’ sensitivity regarding the trawling efficiency of the fleet as well as fish abundance (fish biomass). If trawlers manage to find better/worse fishing grounds than the sample vessels or the fish abundance will increase/decrease, the amount of fish passing the trawl will vary.

Table 3. Sensitivity regarding amount of fish passing the trawl per hour

	Size distribution		
PTT = PTT - 25%	1990s	2000s	2010s
Bacoma 120/105 (Ref)	1	1	1
Bacoma 120/130	0,99	0,95	0,79
PTT unchanged			
Bacoma 120/105 (Ref)	1	1	1
Bacoma 120/130	1,00	0,98	0,91
PTT = PTT + 25%			
Bacoma 120/105 (Ref)	1	1	1
Bacoma 120/130	1,00	0,99	0,95

The reference trawl Bacoma 120/105 performs equal to, or better, than the Bacoma 120/130 codend in all scenarios. The difference between the trawls is dependent on both the PTT and the size distribution. With a larger share of large cod in the stock (1990s distribution) the more selective Bacoma 120/130 performs better as compared to stocks with ha larger share of cod close to the MLS (2010s distribution). Further, the more cod that passes through the trawl (higher PTT) the better the 120/130 codend performs. Thus, the more selective trawl never performs better than the reference trawl, but with higher abundance and/or more large cod the differences are expected to be reduced.

Medium-term forecast as a result of increased selectivity

The medium-term forecast suggests that the Bacoma 120/130 codend would result in a slightly higher (approx. 1 % 2017) SSB irrespectively of recruitment type assumed (Fig. 7).

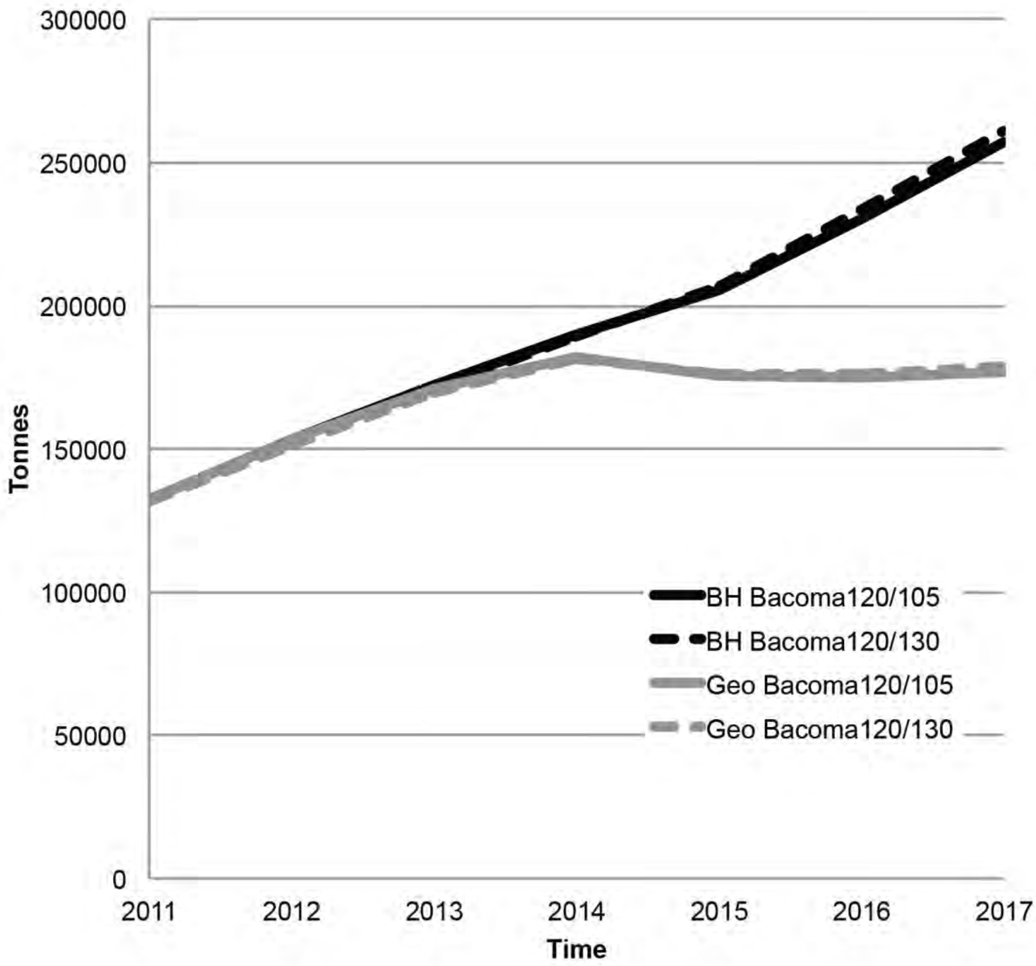

Figure 7. The development of the spawning biomass for the Bacoma 120/105 (Ref) codend and the Bacoma 120/130 codend using geometric mean recruitment (Geo) and recruitment as estimated by fitting a Beverton & Holt stock and recruitment function (BH) on the whole time series (1966-2012).

The use of a Bacoma 120/130 codend will also result in higher (6-8 % depending on recruitment 2017) catches compared to the Bacoma 120/105 (Ref) codend except for the initial year (Fig. 8 & 9). A shift from Bacoma 120/105 (Ref) to Bacoma 120/130 will introduce a decrease in catches the first year after the introduction.

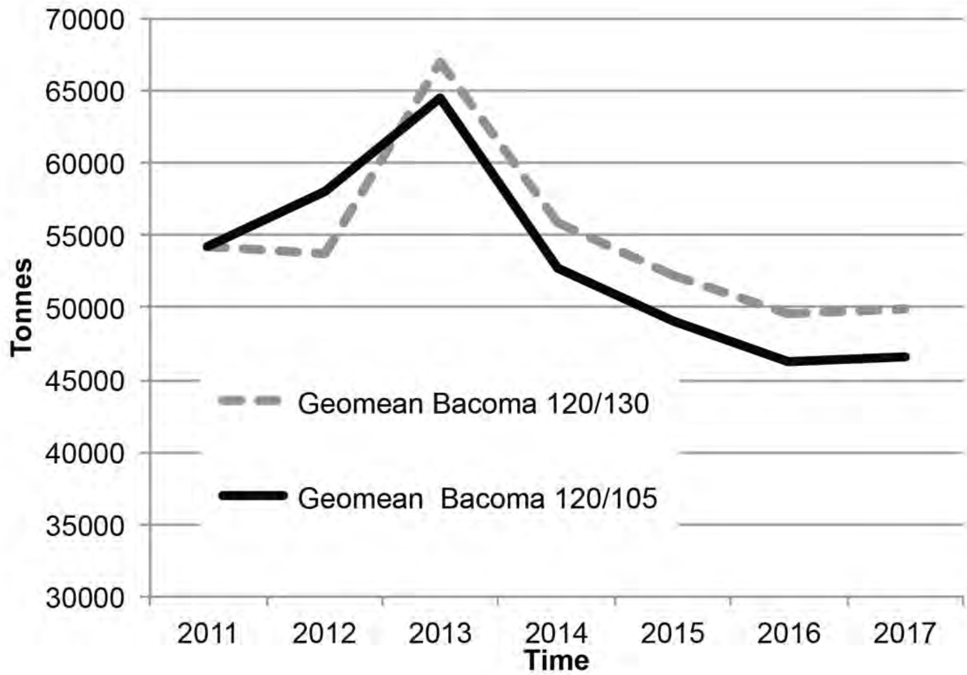

Figure 8. Estimated catches in tonnes using geometric mean recruitment for the Bacoma 120/130 and the Bacoma 120/105 (Ref) codend.

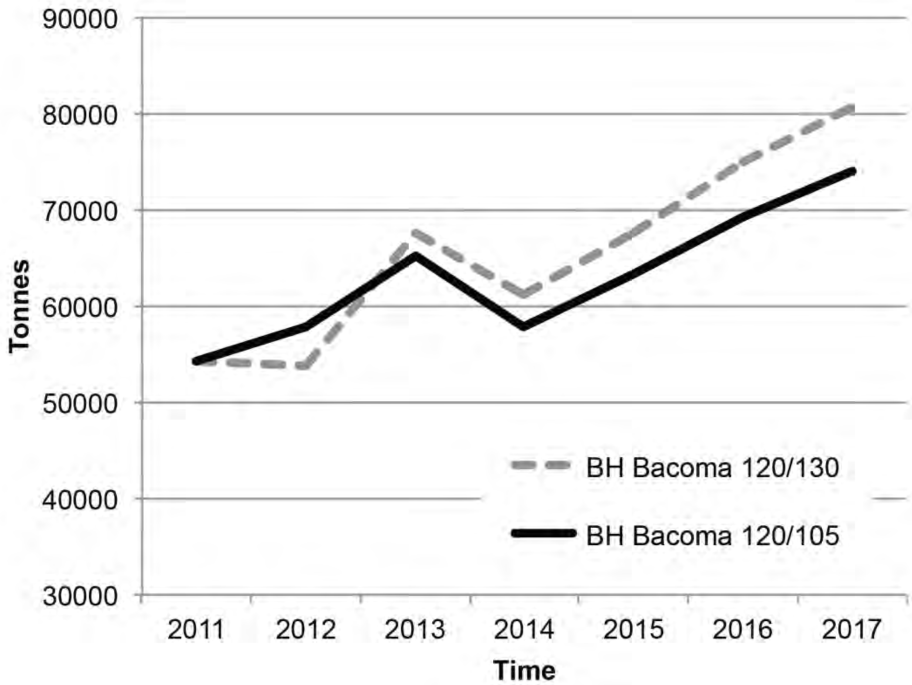

Figure 9. Estimated catches for the Bacoma 120/130 and the Bacoma 120/105 (Ref) codend using recruitment as estimated with by a Beverton & Holt stock and recruitment curve based on the whole time series (1966-2012).

The more selective Bacoma 120/130 codend also suggested that the number of fish per age class in the stock would increase (all ages, 1%) compared to status quo selection (i.e. Bacoma 120/105 codend, Figure 10). The results, even if they should be treated with caution as they are only a forward projection based only on Swedish data and on only trawlers, suggest that a shift to a more selective gear would result in a loss in catch the first year, but this is compensated quickly by an increase in catch weight at age and higher catch number of fish at age.

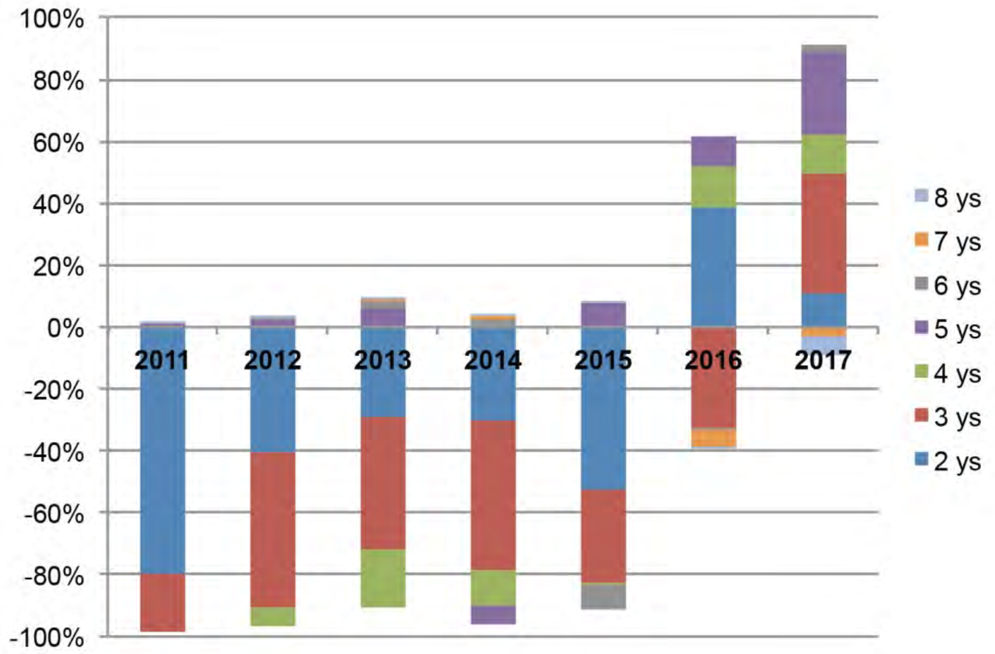

Figure 10. The difference in numbers at age in the stock for the Bacoma 120/105 (Ref) codend and the Bacoma 120/130 codend using recruitment as estimated with by a Beverton & Holt stock and recruitment curve based on the whole time series (1966-2012). A positive value (above 0%) suggests that the Bacoma 120/130 codend has resulted in more fish at age compared to a Bacoma 120/105 codend.

Discussion

We studied the short-term economic outcome of totally 60 scenarios that were divided by four main factors including: gear selectivity, altered MLS, the impact of a discard ban with fixed quota, and stock size class distribution. As a reference, we used the Bacoma 120/105 trawl, MLS 38cm, no discard ban and the latest stock size class distribution (2010s) as baseline for the economic performance. The Gross value added for the reference situation was €264 thousand. This shall cover labour and capital costs as well as profit. To make these results comparable to other economic studies of Swedish Baltic Sea cod trawlers, the resource rent for the reference trawl is calculated. This is done by deducting the labour and capital costs at their alternative use from the Gross Value Added. This generated a resource rent of approximately 13 % of the landing value and Waldo et al (2010) found the resource rent for the Baltic cod trawl fishery to be 10 % of landing value in 2007 based on accounting statistics.

On average, the largest effect on the economic performance of a Swedish standard vessel was obtained by the size class distribution (with up to 71% greater outcome for 1990s distribution compared to 2010s on average), followed by gear selectivity (with up to 11% greater outcome with the T90 codend compared to Full square codend on average), changed MLS (11% greater outcome with MLS35cm compared to 38cm on average) and finally the discard ban (8% higher outcome with no discard ban on average). The reduction in direct economic performance induced by a discard ban is a result of a decreased fishery, since the quota is deducted both from catches below MLS and above MLS, and because quota will be reached earlier with a discard ban. An increased TAC in the future depending on reduced fishing mortality could theoretically compensate this in the future, but this is of course valid for every technical measure resulting in a reduced discard rates (e.g. increased selectivity). However, there might be a resistance to implement discard reduction measures depending on the fisheries expected short term losses and a low confidence in the projected medium and long-term gains (Catchpole et. al. 2005).

A major reason for the current discard problem in the Baltic cod fishery is the size class distribution of the Baltic cod stocks (in combination with the current technical regulations). This is especially true for the eastern Baltic cod stock which has a very stunted size distribution, partly because the legal gears used in the cod trawl fishery today (Bacoma 120/105mm and T90 120mm). Only a small part of the eastern Baltic cod stock has a length above 48cm today (see Figure 1, about 15% in weight, SD25 2010s). This view is also confirmed by the landing statistics; more than 85% of all commercial landed catches of cod in the Swedish trawl fishery in SD25 in 2012 is < 48cm, the smallest EU commercial size category (Swedish landing statistics reported to ICES, DCF).

In this study, the estimated average discarded rates (retained individuals below MLS 35 and 38 cm, independent of a discard ban or not) in SD 25 varied between, 4.2% and 16% depending on time periods, 7.3% and 12% depending on gear selectivity, 4.2% and 15% depending on MLS. During the 1990s the discard rates were reported to be higher than the estimated discard rates for that period in this study. However, this could be explained by the less selective gear used at the time (Diamond mesh 105mm, before 1995, Suuronen et. al. 2007). Still, an observed discard rate of 25% 2012 is to be considered high for a single species fishery

The timing of an introduction of a more selective gear (i.e. increased L50) is important for how it will affect the economic performance of the industry. Figure 4 indicates that a change in gear regulation with a size class distribution as observed during 1990s will only have a minor effect on the economic performance of the fleet, however the same gear regulatory change during 2010s would have a rather significant effect. This is related on the relatively higher loss of individuals just above 38cm in the 2010s scenario due to an overall smaller size distribution in 2010s compared to 1990s. This result suggests that increased selectivity is less costly when a smaller part of the stock is within the size classes of the selective range of suggested gear. This is a general phenomenon and does not imply that selectivity should not be increased under premises of high discards and a corresponding loss in economic performance and outweigh the benefits of reduced discard rates.

The medium-term forecast suggests that changed gear selectivity from Bacoma 120/105 to Bacoma 120/130 will only be slightly positive for the stock biomass, as whole, even though the more selective gear will change the size distribution toward larger cod. From an catchability point view for the fishery, a more selective gear would result in a short time loss (as in the example above) as the catch of smaller sized cod will be reduced but this drop in initial catch would be compensated after approximately 1 year, which suggests that increased selectivity can be positive on a longer time scale (see Cardinale and Hjelm 2012). The results derived from the medium term forecast is highly dependent on the weight at age and could be more positive if weight at age observed right now would increase and the opposite would happen if weight at age would decrease.

Conclusion

- If a discard ban would be introduced today, with current size distribution (period 2010) and with the current legislation (MLS 38cm, Bacoma 120/105 or T90 120), it would result in deceased economic performance (about 20%, see table 2).
- A reduced minimum landing size (MLS: from 38 to 35cm) is a possible way to minimize the negative economic effect of a discard ban.
- The most important single factor affecting the industry's economic performance was the size distribution of the cod stock, but management only indirectly influences this factor.
- The economic performance is in most cases lower when using selective gear compared to the Bacoma 120/105 reference trawl, but the differences in economic performance tends to be smaller when a discard ban is introduced.
- The industry's short term economic loss for increasing selectivity is smaller when the size distribution of cod is "good" (i.e. more large cod is present in the stock), irrespectively of a discard ban is introduced or not.
- The payback time in terms of catch of improved selectivity in the current state of the ecosystem is approximately a year given the current growth rate of the cod stock.

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Annex 4:
The influence of twine thickness, twine number and netting orientation on codend selectivity

Preface

The research presented here, was partly funded within this project. The analysis and writing was conducted in close cooperation between with Bent Herrmann (formerly DTU-Aqua, now SINTEF) after the time he left DTU-Aqua.

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The influence of twine thickness, twine number and netting orientation on codend selectivity

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Abstract

Based in an experimental Baltic trawl fishery, we tested diamond mesh codends with different twine thicknesses, twine numbers (single or double), and netting orientation (T0 or T90) to quantify the effects of the twine characteristics on the size selection of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). For a given twine thickness: going from T0 to T90 increases selectivity of cod; while going from single to double reduce it. Increasing twine thickness reduces selection but the extent depends on whether the twine is single or double and whether the netting orientation is T0 or T90. In general, the results demonstrate the benefit of using a relatively thin single twine netting to ensure the appropriate size selection with round fish and the best results were obtained using netting with a T90 orientation. For a given twine thickness going from T0 to T90 decreases selectivity of plaice. Increasing twine thickness reduces selection for plaice. Our results demonstrate that very different selectivity results can be obtained using the same mesh size, simply by varying the twine

thickness, the twine number, and the netting orientation. In some fisheries, the size selectivity could be improved considerably by adjusting these simple design parameters alternatively to produce more advanced and complex designs.

Keywords: cod, codend selectivity, diamond mesh, plaice, SELNET, size selectivity, T0, T90, twine thickness, twine number

Introduction

Because of its simplicity of construction and ease of operation, diamond mesh codends have traditionally been used to fish for round fish such as cod and haddock (*Melanogrammus aeglefinus),* and flatfish species such a plaice, at the aft end of demersal trawls in northern European fisheries (Graham et al., 2007; O'Neill and Herrmann, 2007; Krag et al., 2008). In recent years, the fishing industry has introduced stronger, stiffer, and thicker twines, which are often used as double twine netting, particularly in the designs of diamond mesh cod-ends used by many European trawl fisheries (Herrmann and O'Neill, 2006). Concerns about their effect on codend size selectivity led to restrictions on the maximum twine thickness and twine number allowed onboard EU fishing vessels. EU regulations, such as 850/1998 and 1967/2006, define the maximum twine thickness permitted in codends used in European waters. The maximum thickness of diamond meshes is 6 mm for double twines and 8 mm for single twine in northern European waters while it is 3 mm in the Mediterranean area. For the size selection of haddock , experimental studies (Lowry and Robertson, 1996; Kynoch et al., 1999) and theoretical studies (Herrmann and O'Neill, 2006; O'Neill and Herrmann, 2007) have demonstrated a significant decrease in the 50% retention length (*L50*) with increasing netting twine thickness for double twine diamond mesh codends. In particular, Herrmann and O'Neill (2006) formulated a set of hypotheses, using the simulation tool PRESEMO (Herrmann, 2005a), to investigate mechanisms that might potentially explain and quantify the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends (T0 cod-ends). The authors reported that an increase in twine thickness could lead to a reduction in selectivity, because: (i) the internal lateral mesh opening of meshes made of thicker twine would be smaller with the same knot-centre to knot-centre lateral mesh opening; (ii) the increased twine bending stiffness of thicker twines would increase the mesh resistance to opening; (iii) it would be more difficult for fish to deform and escape via partly open meshes compared with those made from stiffer twine; and (iv) netting made from thicker twine would present a greater visual barrier to fish, which may discourage them from making escape attempts. Thus, the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends have been well described in the scientific literature, based on experimental and theoretical investigations. From a mechanistic perspective, the effect of twine thickness on haddock size selection using double twine diamond mesh codends can probably be extrapolated to predict and understand the size selection of morphologically similar round fish species such as cod. However, this extrapolation is less likely to be applicable to flatfish species such as plaice, which has a very different cross-sectional shape compared with round fish species. In Baltic Sea trawl fisheries that target cod, the codends made solely from traditional diamond mesh netting has been banned in the legislation since 2003, while it is legal to use diamond mesh netting in combination with square meshes in the BACOMA design and codends where the diamond mesh netting direction is turned 90° (T90)(EU Regulation no. 2187/2005). The T90 codend, which for cod, is believed to have better size selectivity properties compared with the traditional T0 cod-end (Dahm, 2004), was introduced as a legal alternative to the BACOMA codend in the Baltic Sea cod trawl fishery during 2005. For a specific type of single twine netting, Wienbeck et al. (2011) have documented improved cod size selective properties when using T90 cod-ends compared with similar T0 cod-ends. However, Wienbeck et al. (2011) cautioned that their results are specific to the type of netting used for the cod-ends in their experiments and they recommended that a systematic study should be conducted to investigate the effects of twine parameters such as thickness and twine number on the size selectivity of T0 and T90 codends. Furthermore, the legislation describing the construction of T90 codends for the Baltic Sea trawl fishery did not define a specific twine thickness, although an upper limit of twine thickness for single and double twine codends was specified (EU Regulation no. 2187/2005 and EU Reg. No 686/2010). It is unknown to what extent the size selectivity properties of the T90 codend vary within the legal ranges for twine thickness below this maximum thickness and to what extent the twine number in the netting is important.

During trawl fishing, the codend meshes are stretched by hydrodynamic drag forces that act primarily on the accumulated catch in the aft (Herrmann, 2005b; Herrmann et al., 2006). However, difference in mechanical properties of the T0 and T90 codends mean that the shapes of their meshes can be very different during fishing, which can influence their size selectivity properties. According to Herrmann et al. (2007), the bending stiffness of the T0 codends mesh bar, which depends on the twine thickness, tends to keep the meshes closed. By contrast, an increased twine bending stiffness will increase the resistance against mesh closing with the T90 netting. Furthermore, the netting knot size, which increases with twine thickness, may also contribute to the benefit of turning the netting by 90°. These effects seem to favor the use of T90 constructions made of thick twine to achieve high L50 values.

However, some mechanisms that influence the effect of the twine thickness on size selection were described by Herrmann and O'Neill (2006), such as the ability of fish to partly deform the mesh bars during escape attempts and the visual barrier, which favors constructions based on thinner twine netting. These potentially counteracting mechanisms make it difficult to predict the overall effect of changing the twine characteristics (twine thickness and number) on the size selectivity of T0 and T90 cod-ends for round and flatfish species.

Given this lack of knowledge, the main aim of this study was to investigate and quantify the effect of twine thickness, twine number (single or double), and the netting orientation on size selectivity. Therefore, we formulated the following research questions: (i) to what extent does the twine thickness in the codend affect the size selection of round fish (cod) and flatfish (plaice)?; (ii) does it matter whether the codend is made of single or double twine netting?; (iii) do these twine characteristics affect the size selectivity of cod and plaice in different ways with the T0 and T90 codends?

Material and methods

Experimental design

To investigate the research questions regarding the effect of twine characteristics on codend size selection, we tested a total of 12 different codends made of six different commercial netting types (Fig. 1). All codends were made of polytit COMPACT netting (EuroRed S.L., Callosa de Segura, http://www.eurored.org). A T0 and a T90 codend were made from each netting type, resulting in six pairs of codends. Three pairs of nets were made of double twine netting (nominal twine diameter 3, 4, and 6 mm), and three pairs were made of single twine netting (nominal twine diameter 4, 6, and 8 mm). The actual twine diameter was estimated by scanning sample pieces of the different nets using a high resolution flatbed scanner and the image analysis facilities in the FISHSELECT program (Herrmann et al., 2009).

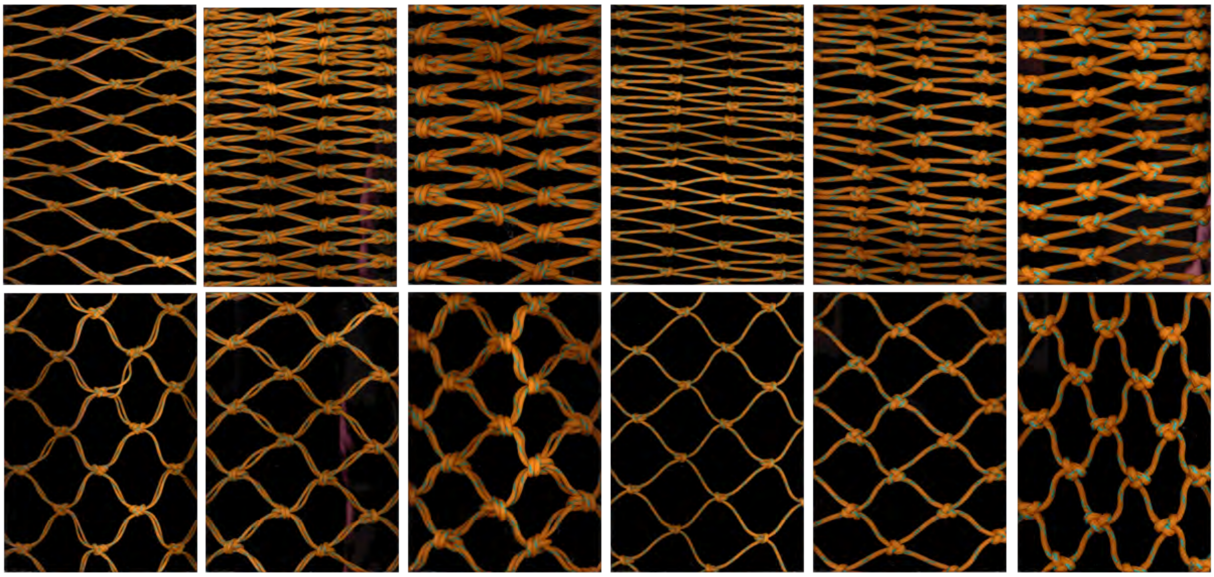

Figure 1: Nettings used for the 12 codends. Top: the six different nettings stretched in the T0 direction. Bottom: the six different nettings stretched in the T90 direction. From left to right: double twine 3 mm (D3), double twine 4 mm (D4), double twine 6 mm (D6), single twine 4 mm (S4), single twine 6 mm (S6), and single twine 8 mm (S8).

All codends were constructed with 50 open meshes in the circumference to comply with the current legislation for the Baltic Sea trawl fishery regarding this design parameter for T90 codends. A symmetrical two-panel construction with identical upper and lower panel was used for all codends. All codends had the same number of meshes in the two selvedges (three). We attempted to keep the mesh size identical for all codends (approximately 123 mm), although it differed slightly between the different nettings. The mesh size was measured using an OMEGA-gauge (Fonteyne et al., 2007; Council Regulation (EC) No 517/2008 of 10 June 2008). Based on their construction and twine characteristics, all of the T90-codends described in Fig. 1 can be used legally in the demersal Baltic Sea trawl fishery.

Each of the 12 codends was fished alternately, one at a time, while attached to the same trawl and the same extension piece. The trawl used was a “Codhopper,” which has a circumference of 530 meshes and a 160 mm mesh size in the belly. The trawl was spread using two 3.5 m^2 Bison trawl doors. The extension piece was a T90 construction with 50 open meshes around and 50 meshes in length, made of nominal 120 mm single 5 mm netting using the same polytit COMPACT netting that was used for the codends. The codend was the only change in gear between the individual tows.

The covered codend method (Wileman et al., 1996) was applied. Supporting hoops were applied to keep the cover netting clear of the test codend. The cover was connected to the extension piece two mesh rows before the codend. The cover was 238 meshes long. The 2.6 m diameter of the cover hoops ensured that the diamond shaped cover meshes were almost open like square meshes. The cover was a two panel construction with a total of 264 meshes in circumference. The cover mesh size was 80 mm because previous experience during experimental fisheries in the same region demonstrated that fishing with a smaller cover mesh size was impossible because of the retention of large amounts of herring in the cover (Wienbeck et al., 2011). Compared with the recommendations of Wileman et al. (1996), this cover mesh size was rather large compared with the test codend mesh sizes (Table 1). Therefore, special attention was given in the analysis to remove length classes where the selection of cover and test codend potentially overlapped. The experimental fishing was conducted onboard the German Fishery Research Vessel (FRV) "Solea" (total length = 42 m, 950 kW). To make the conditions as similar as possible for each codend, all hauls were conducted on the same fishing ground.

Table 1: Specification of the different cod-ends used in this experiment. Each codend name is based on the netting orientation (T0 or T90) and the twine characteristics (see Fig. 1). The parameters TD, DO, T90, and codend category were used in the analysis.

Codend	Mesh size (mm)	td : twine diameter (mm)	DO : double twine	T90 : netting turned 90°	CC: codend category
T0S4	125.4	3.89	0	0	$T0_{single}$
T0S6	124.2	5.72	0	0	$T0_{single}$
T0S8	124.4	7.40	0	0	$T0_{single}$
T0D3	125.3	3.10	1	0	$T0_{double}$
T0D4	123.4	3.66	1	0	$T0_{double}$
T0D6	123.2	5.49	1	0	$T0_{double}$
T90S4	125.4	3.89	0	1	$T90_{single}$
T90S6	124.2	5.72	0	1	$T90_{single}$
T90S8	124.4	7.40	0	1	$T90_{single}$
T90D3	125.3	3.10	1	1	$T90_{double}$
T90D4	123.4	3.66	1	1	$T90_{double}$
T90D6	123.2	5.49	1	1	$T90_{double}$

Data analysis

To model the size selection of cod and plaice for the individual hauls, we used a logistic curve described by the parameters *L50* and the selection range *SR* (= *L75* - *L25*) (Wileman et al., 1996). The capacity of the logistic curve for modeling the data from individual hauls was inspected based on the fit statistics, i.e., the *p*-value and model deviance versus the DOF degrees of freedom (DOF), following the procedures described by Wileman et al. (1996). In case of a poor fit statistic (*p*-value > 0.05; deviance >> DOF), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using the logistic curve or if it was due to the overdispersion of the data. To be able to quantify the strength of the data linked to the amount of binominal noise within it, the R^2-values were also calculated to the ability of the logistic model to describe the experimental data. The R^2-value quantifies the ratio of the variation in the data explained by the model to the total amount of variation in the data. To avoid potential bias in the analysis due to cover selection, the data for length classes below 33 cm were not used for cod, following the procedure described by Wienbeck et al. (2011).

The same method for checking the potential bias due to the cover selection, which as described for cod by Wienbeck et al. (2011), was also applied to plaice prior to the experiments. This found that it is unlikely that any of the available sizes of plaice (> 14 cm) would have passed through the cover meshes. Therefore, no plaice length classes were eliminated from the data analysis. To account for the effect of minor differences in mesh sizes between the different codends (Table 1), the analysis was based on the selection factor *SF* (= *L50/mesh size*) and selection ratio *SFA* (= *SR/mesh size*), instead of *L50* and *SR*. Therefore, the results from single hauls were transformed from an L50-SR domain to an SF-SFA domain, before the next steps in the analysis (Herrmann and O'Neill, 2006). After the last step in the analysis, the results can be transformed back to the traditional L50-SR domain by multiplying with the specific mesh size. This makes the results directly comparable for the different codends with the different twine characteristics (twine thickness, twine number, and netting orientation).

The data were analyzed using the software tool SELNET. SELNET is a flexible software tool that was developed to acquire and analyze size selectivity and catch data for towed fishing gears, both at the haul level and for a group of hauls. The methods implemented in SELNET comply with the recommendations for the analysis of size selectivity data, which were described by Wileman et al. (1996) and in Fryer (1991). SELNET was developed by the corresponding author of the current study and additional information on SELNET can be obtained directly from him or by consulting the following references (Sistiaga et al., 2010; Wienbeck et al., 2011; Frandsen et al., 2011; Eigaard et al., 2011; Herrmann et al., 2012).

The analysis applied considered the between-haul variation in the selection process and the effect of codend design parameters, following the procedure described by Fryer (1991). This involves a two-step procedure, as follows. First, analyzing the hauls individually by fitting a logistic curve to the data, as described above. The second step uses the results from all the individual hauls simultaneously for the *SF* and *SFA,* together with their covariance matrix and information on the values of the design parameters *td (twine thickness in mm)*, *DO (double twine:0.0 for single twine netting; 1.0 for double twine netting),* and *T90* (T90 orientation: 0.0 for T0 orientation netting; 1.0 for T90 orientation netting) for the codends used in each of the hauls. The data were analyzed species by species, while considering the codend design parameters *td*, *DO,* and *T90* as potential fixed effects for *SF* and *SFA* (see Table 1). A special model with the following form was constructed and applied in SELNET (see appendix for model development and justification).

$$SF = f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2 + f_9 \times w$$

$$SFA = g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2 + g_9 \times w$$

(1)

Compared with equation (A4) in the appendix, this equation: (1) includes additional linear terms ($f_9 \times w$ and $g_9 \times w$) to model the potential general linear effect of the codend catch weight on the codend size selection. W is the total codend catch weight at end of the haul. The codend catch weight is included in the model as a potential fixed effect because it is expected to vary between individual hauls and because some authors have found that it can potentially affect the codend size selection in diamond mesh codends (O'Neill and Kynoch, 1996; Herrmann, 2005b). Thus, equation (1) is used to model the effect of the twine characteristics on the *SF* and *SFA* for different codends, while accounting for the potential general effect of the codend catch weight. The species-specific parameters $f_0 \ldots f_9$ and $g_0 \ldots g_9$ have to be estimated while fitting the model to datasets with values for SF and SFA, based on the experimental selectivity results from the individual hauls. Model selection was performed for each species separately based on the AIC value (Akaike, 1974), while considering every possible simpler sub-model following the procedure described in Wienbeck et al. (2011). This resulted in a total of 1048576 models that needed to be run and tested for each species in SELNET.

Before making conclusions regarding the effects of twine thickness and twine number for cod and plaice based on the selected models, it was important to check that the models agreed with the results from the individual hauls, on which they were based. Thus, we considered the uncertainty of the individual results and inspected whether the model prediction appeared to reflect the main trends for the effects of twine thickness on the results for each codend category: $T0_{single}$ (DO=0;T90=0), $T0_{double}$ (DO=1;T90=0), $T90_{single}$ (DO=0;T90=1), and $T90_{double}$ (DO=1;T90=1) (see Table 1). The individual codends used in the experiments did not have the same mesh opening. Therefore, it was also necessary to follow the trends in the L50 and SR values for the individual codends to calculate the corresponding *L50* and *SR* values for a theoretical 120-mm mesh opening simply by multiplying the individual *SF* and *SFA* values by 12. The corresponding confidence limits (CI) for the individual codends were also determined simply by multiplying the lower and upper limit values for the *SF* and *SFA* by 12. The estimates for a mesh size of 120 mm were of particular interest for the Baltic Sea trawl fishery, because this is the minimum legal mesh opening for the T90 codend used in that fishery. After inspecting whether the results from the individual hauls conflicted with the model predictions, it was necessary to consider the estimates of the between-haul variation in the selection process in addition to the uncertainty of the haul results. Therefore, the individual haul results were plotted for the *L50* and *SR* with 95% CI versus the mean model estimated values and the predicted 95% CI for the between-haul variation. The lower and upper 95% CI for the estimated between-haul variation in the selection parameters (lim L50, lim SR) for a mesh size of 120 mm were calculated by:

$$lim\ L50 = 12 \times \left(SF \pm 1.96 \times \sqrt{D_{11}}\right)$$

$$lim\ SR = 12 \times \left(SFA \pm 1.96 \times \sqrt{D_{22}}\right) \quad (2)$$

where *SF* and *SFA* are the predictions based on the selected submodel based on (1), and D_{11} and D_{22} are the diagonal elements in the estimated between haul-variation matrix for the selected model (for details see Fryer, 1991).

The effect of turning the net orientation by 90° from T0 to T90 with the different codend categories ($T0_{single}$, $T0_{double}$, $T90_{single}$ and $T90_{double}$) was given as a percentage effect (p_T90) for the 120 mm nominal mesh opening. The mean percentage effect for L50 (p_T90_{L50}) was predicted using the resulting submodels (1) with the parameters DO and T90 for a range of twine thickness values *td* to estimate the pairs of *L50* for the T0 and T90 designs:

$$p\_T90_{L50} = \frac{L50_{T90} - L50_{T0}}{L50_{T0}} \times 100 \qquad (3)$$

A similar approach was used for *SR*.

Results

Collection of selectivity data

The experimental fishing trials were conducted between 18 March and 7 April 2011 in the Arkona Basin, western Baltic Sea. The water depths varied between 32 and 49 m in the fishing grounds. The average towing speed (GPS speed over ground) was 3.4 knots (range of 3.2–3.6 knots). The haul duration was between 90 and 180 min (mean = 150.2 min). The size selectivity data for cod and plaice were collected from a total of 43 valid hauls. The catch information for each haul are described in Table 2. In addition to cod and plaice, the most abundant catch species in the codend catch was flounder (*Platichthys flesus*) while the cover catch also contained large quantities of herring and sprat. The total catch weight in the codend varied from 180 to 1266 kg. A total of 64376 cod measuring between 13 and 103 cm were caught and their lengths were measured to the nearest cm. We used 47276 cod measuring >33 cm and their data in the analysis. For plaice the length span was 14 to 50 cm and a total of 13760 were caught and measured. The total number of cod (>33 cm) in the test codend ranged from 130 to 1370 individuals, and from 155 to 2253 in the cover. The number of plaice in the test codend ranged from 42 to 319 and from 52 to 420 in the cover. The high number of target species (cod and plaice) caught in most hauls, combined with no subsampling provided strong data for cod in particular, with very little binominal noise in the size selection data.

Table 2: Catch data for individual hauls

Haul No.	Codend	Total codend catch (kg)	Cod: Codend catch (kg)	Cod: No. length classes	Cod: Min length (cm)	Cod: Max length (cm)	Cod: Total no.	Cod: No in codend	Cod: No. in cover	Plaice: Codend catch (kg)	Plaice: No. length classes	Plaice: Min length (cm)	Plaice: Max length (cm)	Plaice: Total no.	Plaice: No. in Codend	Plaice: No. in cover
1	T90D4	422	321	34	33.5	80.5	1201	370	831	33	25	16.5	44.5	217	152	65
2	T90D4	844	727	36	33.5	79.5	3057	804	2253	30	24	16.5	39.5	264	152	112
3	T90D4	375	269	33	33.5	102.5	1118	364	754	18	21	16.5	39.5	262	99	163
4	T90D4	251	171	29	33.5	64.5	965	209	756	21	23	17.5	46.5	181	99	82
5	T90S4	427	271	30	33.5	72.5	1362	340	1022	34	25	17.5	46.5	303	159	144
6	T90S4	284	135	23	33.5	62.5	521	188	333	29	24	15.5	40.5	380	125	255
7	T90S4	434	329	32	33.5	74.5	1851	350	1501	21	24	16.5	39.5	209	88	121
8	T90S4	423	300	29	33.5	65.5	1598	358	1240	23	21	15.5	36.5	282	105	177
9	T90D6	572	357	22	33.5	58.5	1053	549	504	53	26	15.5	42.5	423	314	109
10	T90D6	546	424	32	33.5	72.5	1250	571	679	31	23	16.5	46.5	232	172	60
11	T90D6	631	404	29	33.5	74.5	1251	557	694	52	24	15.5	47.5	438	327	111
12	T90D6	461	288	25	33.5	58.5	788	405	383	41	24	16.5	42.5	392	233	159
13	T90S6	595	478	29	33.5	72.5	1909	608	1301	25	26	16.5	45.5	192	134	58
14	T90S6	573	410	30	33.5	71.5	1638	523	1115	48	23	16.5	41.5	475	263	212
15	T90S6	281	153	22	33.5	54.5	503	216	287	33	24	16.5	40.5	343	191	152
16	T90S6	346	284	28	33.5	71.5	1881	384	1497	21	23	16.5	40.5	224	98	126
17	T90D3	430	283	26	33.5	58.5	1460	349	1111	44	26	16.5	43.5	439	222	217
18	T90D3	299	149	24	33.5	79.5	618	205	413	36	22	15.5	37.5	429	188	241
19	T90D3	386	227	30	33.5	80.5	951	264	687	30	25	16.5	42.5	371	135	236
20	T90D3	219	159	27	33.5	66.5	589	185	404	13	23	17.5	42.5	123	52	71
21	T90S8	243	176	26	33.5	61.5	526	209	317	22	28	16.5	44.5	198	90	108
22	T90S8	529	418	31	33.5	63.5	1539	479	1060	41	27	16.5	43.5	290	218	72
23	T90S8	315	160	26	33.5	67.5	672	221	451	44	21	15.5	37.5	474	302	172
24	T90S8	713	147	27	33.5	65.5	512	155	357	23	24	17.5	42.5	177	125	52
25	T0D4	364	305	27	33.5	74.5	874	410	464	20	25	17.5	46.5	199	73	126
26	T0D4	428	348	28	33.5	61.5	965	447	518	23	28	15.5	48.5	213	78	135
27	T0D4	280	224	26	33.5	63.5	567	293	274	16	24	17.5	42.5	157	57	100
28	T0S4	273	233	27	33.5	62.5	488	295	193	12	21	17.5	37.5	137	47	90
29	T0S4	180	123	25	33.5	92.5	516	130	386	11	23	17.5	39.5	113	42	71
30	T0S4	363	245	28	33.5	71.5	1343	273	1070	26	23	16.5	39.5	360	103	257
31	T0S4	302	176	27	33.5	63.5	817	192	625	34	27	14.5	43.5	450	137	313
32	T0D3	272	192	21	33.5	55.5	837	255	582	26	26	16.5	42.5	397	102	295
33	T0D3	234	180	27	33.5	60.5	792	227	565	14	22	16.5	39.5	219	49	170
34	T0D3	326	187	24	33.5	76.5	505	270	235	32	25	14.5	40.5	500	130	370
35	T0S8	798	542	29	33.5	68.5	1055	836	219	28	25	16.5	43.5	457	120	337
36	T0S8	474	384	28	33.5	63.5	862	561	301	16	25	16.5	42.5	214	152	62
37	T0S8	598	401	30	33.5	83.5	792	577	215	35	26	15.5	42.5	339	250	89
38	T0S8	604	423	26	33.5	72.5	975	641	334	24	25	17.5	43.5	365	272	93
39	T0D6	922	717	30	33.5	65.5	1250	1095	155	25	25	15.5	49.5	396	124	272
40	T0D6	1266	937	31	33.5	73.5	1810	1370	440	49	25	16.5	41.5	683	263	420
41	T0D6	1057	788	29	33.5	69.5	1338	1055	283	33	26	14.5	41.5	477	158	319
42	T0S6	586	479	28	33.5	73.5	1618	662	956	27	24	15.5	38.5	413	124	289
43	T0S6	461	360	26	33.5	60.5	1059	552	507	24	24	16.5	46.5	353	110	243

Table 3: Estimation of the selection parameters and fit statistics for individual hauls of cod

Haul No.	Codend	L50 (cm)	SR (cm)	SF	SFA	*P*-value	Deviance	DOF	R^2-value
1	T90D4	41.94	7.21	3.40 (3.35-3.45)	0.58 (0.50- 0.67)	0.9709	18.66	32	0.9823
2	T90D4	42.54	5.38	3.45 (3.42- 3.47)	0.44 (0.40- 0.47)	0.7917	27.15	34	0.9941

3	T90D4	41.22	6.99	3.34 (3.29- 3.39)	0.57 (0.48- 0.65)	0.5890	28.62	31	0.9759
4	T90D4	43.61	7.43	3.53 (3.44- 3.63)	0.60 (0.47- 0.73)	0.0202	44.10	27	0.9045
5	T90S4	42.58	7.79	3.40 (3.34- 3.46)	0.62 (0.53- 0.72)	0.9008	18.91	28	0.9734
6	T90S4	39.86	6.16	3.18 (3.12- 3.24)	0.49 (0.39- 0.60)	0.9833	9.63	21	0.9646
7	T90S4	45.63	8.31	3.64 (3.57- 3.70)	0.66 (0.58- 0.75)	0.5403	28.57	30	0.9688
8	T90S4	43.62	6.43	3.48 (3.43- 3.52)	0.51 (0.45- 0.57)	0.8521	19.47	27	0.9867
9	T90D6	37.21	5.37	3.02 (2.99- 3.05)	0.44 (0.37- 0.50)	0.7376	15.66	20	0.9834
10	T90D6	38.24	4.43	3.10 (3.08- 3.13)	0.36 (0.31- 0.40)	0.9999	8.92	30	0.9954
11	T90D6	38.23	5.10	3.10 (3.07- 3.13)	0.41 (0.36- 0.47)	0.9292	17.08	27	0.9852
12	T90D6	37.45	4.70	3.04 (3.01- 3.07)	0.38 (0.32- 0.44)	0.9943	9.43	23	0.9873
13	T90S6	41.25	6.69	3.32 (3.29- 3.36)	0.54 (0.48- 0.60)	0.7697	21.35	27	0.9850
14	T90S6	41.22	6.29	3.32 (3.28- 3.35)	0.51 (0.45- 0.57)	0.9575	16.52	28	0.9905
15	T90S6	39.09	7.04	3.15 (3.09- 3.21)	0.57 (0.44- 0.70)	0.1606	26.16	20	0.8517
16	T90S6	41.83	5.19	3.37 (3.33- 3.41)	0.42 (0.37- 0.47)	0.9397	15.85	26	0.9748
17	T90D3	42.48	7.18	3.39 (3.34- 3.44)	0.57 (0.49- 0.65)	0.7752	18.56	24	0.9789
18	T90D3	39.71	4.81	3.17 (3.13- 3.21)	0.38 (0.31- 0.45)	0.5560	20.43	22	0.6846
19	T90D3	41.33	6.03	3.30 (3.25- 3.35)	0.48 (0.41- 0.56)	0.7348	22.96	28	0.9768
20	T90D3	42.37	7.68	3.38 (3.31- 3.46)	0.61 (0.49- 0.73)	0.9416	14.99	25	0.9466
21	T90S8	40.36	5.19	3.24 (3.20- 3.29)	0.42 (0.34- 0.49)	0.9835	11.66	24	0.9892
22	T90S8	41.21	5.92	3.31 (3.28- 3.35)	0.48 (0.42- 0.53)	0.5791	26.86	29	0.9792
23	T90S8	40.04	7.20	3.22 (3.15- 3.28)	0.58 (0.46- 0.70)	0.9049	15.51	24	0.9540
24	T90S8	41.82	4.80	3.36 (3.31- 3.42)	0.39 (0.31- 0.46)	0.9008	16.45	25	0.9835
25	T0D4	38.88	7.96	3.15 (3.10 - 3.20)	0.65 (0.53- 0.76)	0.9990	8.69	25	0.9816
26	T0D4	39.51	7.25	3.20 (3.16- 3.24)	0.59 (0.49- 0.68)	0.4697	25.88	26	0.9188
27	T0D4	38.79	7.69	3.14 (3.09- 3.20)	0.62 (0.49- 0.76)	0.9990	8.09	24	0.9812
28	T0S4	37.91	8.65	3.02 (2.95- 3.09)	0.69 (0.52- 0.86)	0.3923	26.29	25	0.8903
29	T0S4	43.21	6.21	3.45 (3.37- 3.52)	0.50 (0.39- 0.60)	0.9967	8.76	23	0.9711
30	T0S4	43.50	6.84	3.47 (3.41-3.53)	0.55 (0.47- 0.62)	0.4783	25.72	26	0.9800
31	T0S4	43.03	6.81	3.43 (3.36- 3.50)	0.54 (0.45- 0.64)	0.7792	19.37	25	0.9518
32	T0D3	40.57	6.46	3.24 (3.18- 3.29)	0.52 (0.42- 0.61)	0.7316	14.86	19	0.9712
33	T0D3	41.83	7.43	3.34 (3.27- 3.41)	0.59 (0.48- 0.70)	0.9435	14.91	25	0.9501
34	T0D3	37.32	8.74	2.98 (2.91- 3.04)	0.70 (0.51- 0.89)	0.7853	16.59	22	0.9255
35	T0S8	29.84	11.08	2.40 (2.22- 2.57)	0.89 (0.60- 1.18)	0.5030	26.28	27	0.8110
36	T0S8	35.00	8.86	2.81 (2.75- 2.88)	0.71 (0.55- 0.88)	0.7583	20.68	26	0.9401
37	T0S8	34.33	6.25	2.76 (2.70- 2.81)	0.50 (0.39- 0.61)	0.9980	11.19	28	0.9713
38	T0S8	34.51	7.44	2.77 (2.73- 2.82)	0.60 (0.47- 0.72)	0.9822	11.79	24	0.9637
39	T0D6	29.97	7.67	2.43 (2.29- 2.57)	0.62 (0.45- 0.79)	0.9999	8.35	28	0.9689
40	T0D6	32.06	9.54	2.60 (2.52- 2.68)	0.77 (0.62- 0.92)	0.9562	17.36	29	0.9628
41	T0D6	30.76	9.98	2.50 (2.38- 2.62)	0.81 (0.61- 1.01)	0.9713	14.86	27	0.9249
42	T0S6	39.60	8.59	3.19 (3.15- 3.23)	0.69 (0.59- 0.79)	0.9320	16.17	26	0.9759
43	T0S6	37.07	8.08	2.98 (2.94- 3.03)	0.65 (0.53- 0.77)	0.3524	26.01	24	0.9414

Analysis of the cod data

As described in section 2.2, a logistic curve was fitted to data from individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values. Table 3 summarizes the results from individual hauls of cod. Inspection of fit statistics indicated that there were no problems with using a logistic curve to describe the selection data for all hauls, except for haul no. 4 (*p*-value = 0.02). The inspection of the residuals for haul 4 did not indicate any structural problems with using the logistic curve to model the experimental data. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about applying the logistic curve to model the size selection of cod in all hauls. In general, high R^2-values were obtained, i.e., all but one was >0.8 and only 4/43 were <0.90 (Table 3). In addition to the capacity of the model for describing the data, these high R^2-values also highlighted the low binominal noise in the data as a consequence of strong data acquisition because many cod were measured and no subsampling was applied.

The values for L50 ranged from 29.84 cm to 45.63 cm, which did correspond to the SF values of 2.40 and 3.64. The highest values were obtained for hauls 7 (T90S4), 1–4 (T90D4), 8 (T90S4), 17 (T90D3), and 29–31 (T0S4) (Table 3). By contrast, low L50 and SF values were determined for haul 35 (T0S8) and hauls 39–41 (T0D6). The range of values for SR and SFA were 4.43 cm to 11.08 cm and 0.36 to 0.89, respectively. Thus except for codend T0D6 the data included in the analysis covered most of the selective range (from zero retention (r(l) = 0.0) to full retention (r(l)=1.0). For T0D6 detail inspection of results showed the data coverage at the lowest length class (33 cm) varied from r = 0.55 to r = 0.70. This increase the uncertainty when evaluating the validity of the logit curve to model the size selection of the full selection curve for this codend design and increase confidence limits for the estimated SF and SFA values (link Table 2 and 3). But given the fact that none of the results for the other codends indicated problems by applying the logit curve to model the size selection in individuals we assume that is this also valid for the T0D6 design even if the SF and SFA values are based on extrapolation of the estimated logit curve. Therefore despite of the poor coverage of the selective range for the hauls with the T0D6 codend we have chosen also to use the results for this codend in the further analysis. This is further defended by that in the further step of the analysis is the uncertainties in the individual hauls accounted for. Specifically is the uncertainty in the individual haul *SF* and *SFA* values modeled as within haul variation and therefore automatically accounted for in the analysis (see Fryer (1991) for further details on this).

To estimate the general effects of the design parameters *td*, DO, and T90 on the codend size selection of cod, we analyzed model (1) and each simpler submodel that could be derived from this model, before comparing them. This evaluation was based on the results for the SF and SFA for all 43 hauls, as described in section 2.2. For cod, this resulted in the following model (model (4)).

$$SF = f_0 + (f_2 + f_6 \times T90 + f_7 \times DO) \times td^2$$

$$SFA = g_0 + g_3 \times T90 \times td \qquad (4)$$

Applying the second model selection step, testing 1023 additional models, as described in appendix to validate using model (1) as basis for the model selection did not result in any changes in the selected model for cod. Therefore we can proceed with model (4) which shows that all three design parameters, i.e., *td*, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between using single and double twine netting, was absent from the best model. Table 4 lists the details of model (4).

Table 4: Results for combined model (4) with fixed and random effects using the method described in Fryer (1991). D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the SF and SFA (for details see Fryer (1991)).

		Multiplier	Value	SE	95% confidence limits	*P*-value
SF	f_0	intercept	3.5228	0.0453	3.4326 – 3.6129	3.8074e-77
	f_2	td^2	-0.0149	1.4441e-3	-0.0178 – -0.0121	2.0449e-16
	f_6	$T90 \times td^2$	0.0106	1.3343e-3	0.0079 – 0.0132	1.2046e-11
	f_7	$DO \times td^2$	-0.0133	1.8633e-3	-0.0170 – -0.0096	4.1584e-10
SFA	g_0	intercept	0.6116	0.0199	0.5720 – 0.6513	5.2094e-46
	g_3	$T90 \times td$	-0.0242	4.8565e-3	-0.0339 – -0.0146	3.4547e- 6
Between -haul variation	D_{11}	1.7361e-2				
	D_{12}	-2.4980e-3				
	D_{22}	4.6925e-3				
Model statistics	Log-likelihood					-303.57
	AIC-value					661.14
	Delta log-likelihood for the estimate					7.5773e-15
	Number of hauls					43

Because f_2 was significantly less than zero (see Table 4), an increase in the twine thickness resulted in a decrease in SF, and thus L50. This effect was much stronger for double twine nettings because the parameter f_7 was close to the value of f_2 and it was also significantly less than zero. Based on the estimated f_6 value, which was significantly larger than zero, turning the netting by 90° would reduce the negative effects of the twine thickness and twine number on the SF and L50. Nevertheless, this T90 effect was not sufficiently strong to fully compensate for both negative effects. Consequently, the overall effect would be a slight decrease in the SF with an increase in the twine thickness.

However, inspecting the confidence intervals for f_2 and f_6 showed that the predicted decrease in SF with an increase in twine thickness for single twined T90 codends was not significant because the upper limit for f_6 was more than the limit for f_2, which was closest to zero. By contrast, for double twine codends, the confidence interval for f_6 did not overlap with the confidence interval for the combined negative effect of f_2 and f_7. Thus, for double twine T90 codends, we estimated that there was a significant decrease in SF with an increase in twine thickness. Because the sum of f_6 and f_7 is also negative, the model predicts a lower SF for a double twine T90 codend compared with a similar T0 single twine with the same twine thickness. This effect was not statistically significant according to Table 4.

For SFA and thus also SR, model (4) predicted no effect of twine thickness for T0 codends ($T0_{single}$ and $T0_{double}$) and no difference in the values for single and double twined T0 codends. For T90 codends, there was a significant decrease in SFA with an increase in twine thickness. The model predicted that this effect would be identical for single and double twine T90 codends. Fig. 2 shows the predicted mean effect on the L50 and SR, depending on the twine thickness for cod in a codend with a 120-mm mesh size based on model (4). Table 4 shows the four different codend categories based on the predicted values for SF and SFA with corresponding rescaling to the L50-SR domain for a mesh size of 120 mm (see section 2.2).

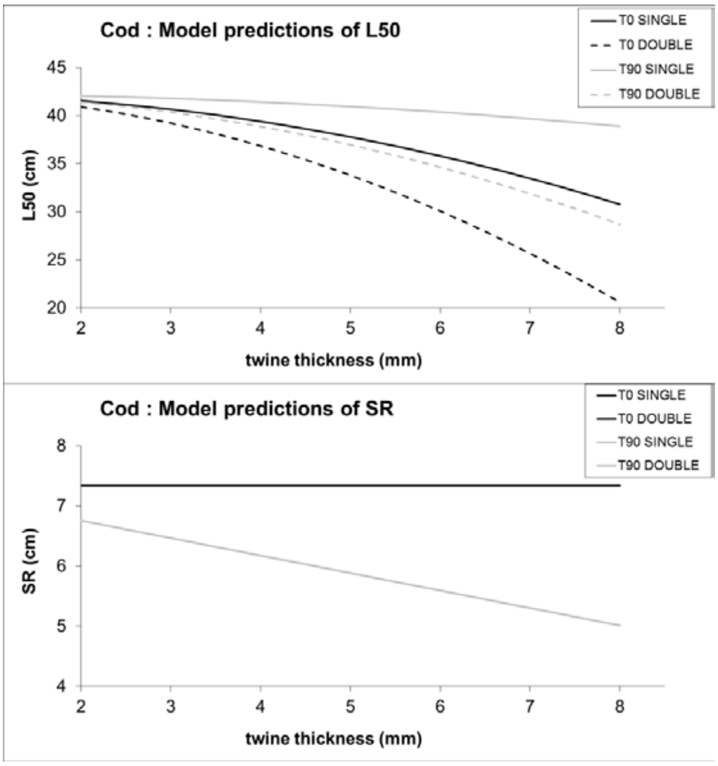

Figure 2: Predicted mean L50 and SR values for cod, depending on the twine thickness. The SF and SFA values were rescaled for a 120-mm mesh size, according to the procedure described in section 2.2. For SR, both T0 and both T90 curves (single and double) are identical according to the model predictions.

Fig. 3 shows the L50 and SR values (rescaled to 120 mm) for the individual hauls for the four different codend categories, depending on the codend twine thickness. The CI for the individual haul parameters are indicated, as well as the predicted between-haul variation in the selection process (see model (2) and Table 4).

For all four codend categories, model (4) could reproduce the main trends of the effect of the twine thickness on L50 and SR, which was found in the experimental results (Fig. 3). None of the results for any of the 43 hauls were found to be in direct conflict with the models for either L50 or SR after inspecting the CI for the estimated values in the individual hauls and for the predicted between-haul variation in the selection process. This further supports our model selection procedure and basis model (section 2.2 and appendix). Thus, we were confident when applying the model to make predictions.

Model (4) was used to predict the effect of an increase in twine thickness on the mean values for L50 and SR with a 120-mm codend mesh size (Table 5). In addition, the percentage effect of turning the netting by 90° (from (T0 to T90) was estimated for different twine thicknesses (see formulae (3))

The percentage effect on L50 by going from T0 to T90 orientation increased with the twine thickness. This was found to have a more profound effect with double twine netting compared with single twine netting. For twine thickness at 2 mm the effect is predicted to be 1.22% for single twine and 1.24% for double twine. For twine thickness at 8 mm the effected is predicted to be 26.33% for single twine and 39.34% for double twine. According to the model, however, this positive effect could not compensate for the negative effect that the increased twine thickness had on the T0 baseline value. For cod, therefore, the model predicted a decrease in the L50 with an increase in the codend twine thickness for T0 and T90 codends. Nevertheless, this effect was not significant for the T90 single twine codends. For the codend category T0 with a single twine, the effect of increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 41.56 cm to 30.80 cm. This was a drop of 10.76 cm, which corresponded to >25%. This effect was more profound with double twine T0 codends, where increasing the twine thickness from 2 mm to 6 mm reduced the L50 by >26%.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 5). Thus, using a thicker twine tended to decrease the SR with T90 codends.

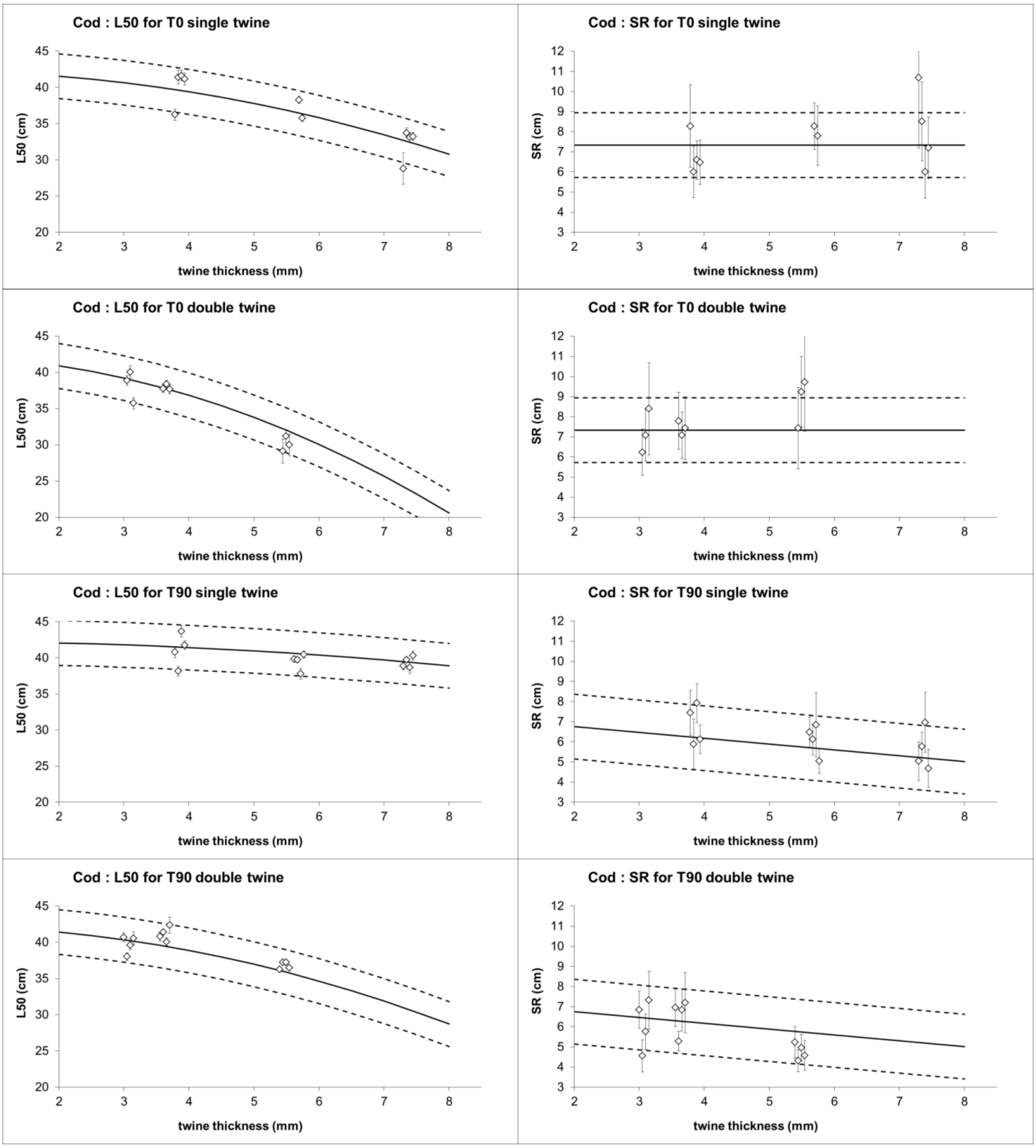

Figure 3: L50 and SR values for cod from single hauls with the different cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which have been rescaled to a 120-mm mesh size.

Table 5: Model predictions for the influence of twine thickness on the size selection of cod in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

	L50 Single Twine			L50 Double Twine			SR Single Twine			SR Double Twine		
td (mm)	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2.0	41.56 (40.57-42.54)	42.06 (41.07-43.05)	1.22	40.92 (40.02-41.82)	41.43 (40.52-42.33)	1.24	7.34 (6.86-7.82)	6.76 (6.23-7.29)	-7.92	7.34 (6.86-7.82)	6.76 (6.23-7.29)	-7.92
2.5	41.15 (40.21-42.09)	41.94 (40.99-42.90)	1.92	40.16 (39.35-40.97)	40.95 (40.12-41.77)	1.97	7.34 (6.86-7.82)	6.61 (6.06-7.17)	-9.91	7.34 (6.86-7.82)	6.61 (6.06-7.17)	-9.91
3.0	40.66 (39.77-41.55)	41.80 (40.88-42.72)	2.80	39.23 (38.51-39.94)	40.37 (39.61-41.12)	2.91	7.34 (6.86-7.82)	6.47 (5.88-7.06)	-11.89	7.34 (6.86-7.82)	6.47 (5.88-7.06)	-11.89
3.5	40.08 (39.24-40.91)	41.63 (40.72-42.53)	3.87	38.13 (37.49-38.76)	39.68 (38.96-40.40)	4.07	7.34 (6.86-7.82)	6.32 (5.70-6.95)	-13.87	7.34 (6.86-7.82)	6.32 (5.70-6.95)	-13.87
4.0	39.40 (38.61-40.20)	41.43 (40.52-42.35)	5.14	36.86 (36.26-37.45)	38.88 (38.13-39.64)	5.50	7.34 (6.86-7.82)	6.18 (5.51-6.84)	-15.85	7.34 (6.86-7.82)	6.18 (5.51-6.84)	-15.85
4.5	38.64 (37.88-39.41)	41.21 (40.23-42.18)	6.64	35.42 (34.78-36.06)	37.98 (37.10-38.86)	7.24	7.34 (6.86-7.82)	6.03 (5.32-6.74)	-17.83	7.34 (6.86-7.82)	6.03 (5.32-6.74)	-17.83
5.0	37.79 (37.02-38.56)	40.96 (39.88-42.03)	8.38	33.81 (33.03-34.59)	36.98 (35.89-38.06)	9.37	7.34 (6.86-7.82)	5.89 (5.13-6.64)	-19.81	7.34 (6.86-7.82)	5.89 (5.13-6.64)	-19.81
5.5	36.85 (36.04-37.66)	40.68 (39.45-41.91)	10.40	32.03 (31.04-33.03)	35.86 (34.51-37.22)	11.96	7.34 (6.86-7.82)	5.74 (4.94-6.54)	-21.79	7.34 (6.86-7.82)	5.74 (4.94-6.54)	-21.79
6.0	35.82 (34.92-36.72)	40.38 (38.96-41.80)	12.73	30.09 (28.82-31.36)	34.65 (32.96-36.33)	15.16	7.34 (6.86-7.82)	5.59 (4.75-6.44)	-23.77	7.34 (6.86-7.82)	5.59 (4.75-6.44)	-23.77
6.5	34.70 (33.67-35.73)	40.05 (38.39-41.71)	15.43	27.97 (26.38-29.56)	33.32 (31.27-35.38)	19.14	7.34 (6.86-7.82)	5.45 (4.56-6.34)	-25.75	7.34 (6.86-7.82)	5.45 (4.56-6.34)	-25.75
7.0	33.49 (32.29-34.68)	39.69 (37.76-41.63)	18.54	25.69 (23.74-27.63)	31.89 (29.42-34.36)	24.17	7.34 (6.86-7.82)	5.30 (4.36-6.24)	-27.73	7.34 (6.86-7.82)	5.30 (4.36-6.24)	-27.73
7.5	32.19 (30.79-33.59)	39.31 (37.07-41.55)	22.14	23.23 (20.89-25.57)	30.36 (27.44-33.28)	30.67	7.34 (6.86-7.82)	5.16 (4.17-6.15)	-29.72	7.34 (6.86-7.82)	5.16 (4.17-6.15)	-29.72
8.0	30.80 (29.17-32.43)	38.90 (36.33-41.48)	26.33	20.61 (17.84-23.37)	28.72 (25.31-32.12)	39.34	7.34 (6.86-7.82)	5.01 (3.97-6.06)	-31.70	7.34 (6.86-7.82)	5.01 (3.97-6.06)	-31.70

Analysis of the plaice data

As with cod, a logistic curve was fitted to the size selection data for plaice captured in individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values for individual hauls. Table 6 summarizes results for individual hauls of plaice. An inspection of the fit statistics indicated that there was no problem with using a logistic curve to describe the selection data for all hauls, except for hauls no. 14 and no. 40 with *p*-values of 0.0029 and 0.0035, respectively. An inspection of the residuals for hauls 14 and 40 did not indicate any structural problems with using the logistic curve to model the experimental data in either of these hauls. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about using the logistic curve to model the size selection of plaice in all individual hauls. Furthermore, the high R^2-values, where the lowest value was 0.74 and only 3/43 values were <0.91, highlighted the power of the data based on the very low binominal noise.

To estimate the general effect of the design parameters *td*, DO, and T90 on the codend size selection of plaice, model (1) and all simpler submodels were analyzed and compared. This evaluation was based on the results for the SF and SFA for all 43 hauls we conducted (see section 2.2). For plaice, this resulted in the following model (model (5)).

$$SF = f_0 + f_1 \times td + f_3 \times T90 \times td + f_5 \times T90 \times DO \times td$$

$$SFA = g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td$$

(5)

Applying the second model selection step, testing 2047 additional models, as described in appendix to validate using model (1) as basis for the model selection did not result in any changes in the selected model for plaice. Therefore we can proceed with model (5) which show that all three design parameters, i.e., td, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between using single and double twine netting, was absent from the best model. Table 7 shows the details for model (5).

Table 7 shows that an increase in the twine thickness (TD) tended to decrease the SF, and thus the L50, for all four categories of codends, because parameter f_1 was significant less than zero. For the T0 types of codends ($T0_{single}$ and $T0_{double}$), the effect was predicted to be identical. For T90 codends, the decrease in SF with an increase in the twine thickness would be even bigger because f_3 and f_5 were significantly less than zero. Thus, the biggest decrease in SF with an increase in the twine thickness was found with the codend type $T90_{double}$ whereas the lowest was with the two T0 codend types.

Table 6: Estimation of the selectivity parameters and the fit statistics for individual hauls of plaice

Haul No.	Codend	L50 (cm)	SR (cm)	SF	SFA	*P*-value	Deviance	DOF	R^2-value
1	T90D4	21.17	1.20	1.72 (1.69- 1.74)	0.10 (0.06- 0.13)	0.9999	5.56	23	0.9929
2	T90D4	22.97	1.56	1.86 (1.83- 1.89)	0.13 (0.08- 0.17)	0.9999	5.28	22	0.9928
3	T90D4	23.22	2.56	1.88 (1.84- 1.93)	0.21 (0.15- 0.27)	0.9994	4.99	19	0.9941
4	T90D4	21.97	1.96	1.78 (1.74- 1.82)	0.16 (0.10- 0.22)	1.0000	1.61	21	0.9971
5	T90S4	22.92	2.91	1.83 (1.79- 1.87)	0.23 (0.18- 0.29)	0.2811	26.43	23	0.9614
6	T90S4	23.91	2.63	1.91 (1.86- 1.95)	0.21 (0.16- 0.26)	0.9846	10.18	22	0.9841
7	T90S4	24.30	1.99	1.94 (1.89- 1.98)	0.16 (0.11- 0.21)	0.9978	7.74	22	0.9917
8	T90S4	24.68	2.80	1.97 (1.92- 2.02)	0.22 (0.17- 0.28)	0.798	13.75	19	0.9899

9	T90D6	20.21	3.62	1.64 (1.60- 1.68)	0.29 (0.22- 0.37)	1.0000	4.33	24	0.9928
10	T90D6	20.54	2.60	1.67 (1.63- 1.71)	0.21 (0.13- 0.29)	0.9831	9.65	21	0.9748
11	T90D6	20.49	2.30	1.66 (1.64- 1.69)	0.19 (0.14- 0.23)	1.0000	4.61	22	0.9965
12	T90D6	21.12	2.46	1.71 (1.69- 1.74)	0.20 (0.15- 0.25)	0.6758	18.5	22	0.9710
13	T90S6	20.41	2.66	1.64 (1.60- 1.69)	0.21 (0.14- 0.29)	0.9967	9.37	24	0.9658
14	T90S6	22.21	3.56	1.79 (1.74- 1.84)	0.29 (0.20- 0.37)	0.0029	43.3	21	0.9373
15	T90S6	22.15	2.30	1.78 (1.75-1.81)	0.18 (0.14- 0.23)	0.9698	11.33	22	0.9914
16	T90S6	22.24	2.35	1.79 (1.75- 1.83)	0.19 (0.13- 0.25)	0.2676	24.54	21	0.9472
17	T90D3	22.66	2.47	1.81 (1.78- 1.84)	0.20 (0.16- 0.24)	0.9996	7.34	24	0.9916
18	T90D3	23.39	3.00	1.87 (1.83- 1.90)	0.24 (0.19- 0.29)	0.6152	17.58	20	0.9813
19	T90D3	23.94	2.97	1.91 (1.87- 1.95)	0.24 (0.18- 0.29)	1.0000	3.18	23	0.9963
20	T90D3	23.29	1.75	1.86 (1.81- 1.91)	0.14 (0.08- 0.20)	0.9978	7.17	21	0.9682
21	T90S8	22.77	2.86	1.83 (1.77- 1.89)	0.23 (0.15- 0.31)	0.9953	11.07	26	0.9706
22	T90S8	20.39	1.96	1.64 (1.61- 1.67)	0.16 (0.11- 0.21)	1.0000	5.02	25	0.9624
23	T90S8	20.83	2.52	1.67 (1.65- 1.70)	0.20 (0.16- 0.25)	0.9235	11.01	19	0.9879
24	T90S8	20.05	3.71	1.61 (1.55- 1.67)	0.30 (0.17- 0.43)	0.9570	12.02	22	0.8886
25	T0D4	25.35	3.34	2.05 (1.99- 2.12)	0.27 (0.19- 0.35)	0.9987	7.77	23	0.9747
26	T0D4	25.25	3.47	2.05 (1.98- 2.12)	0.28 (0.20- 0.36)	0.0657	37.61	26	0.7384
27	T0D4	24.93	3.11	2.02 (1.94- 2.10)	0.25 (0.17- 0.34)	0.7760	16.77	22	0.9369
28	T0S4	24.60	2.16	1.96 (1.89- 2.03)	0.17 (0.10- 0.24)	0.9957	6.70	19	0.9756
29	T0S4	25.82	2.73	2.06 (1.97- 2.15)	0.22 (0.13- 0.30)	0.9758	10.23	21	0.9177
30	T0S4	26.58	2.95	2.12 (2.07- 2.17)	0.24 (0.18- 0.29)	0.9803	9.89	21	0.9894
31	T0S4	26.52	3.04	2.11 (2.08- 2.15)	0.24 (0.19- 0.29)	0.5398	23.65	25	0.9838
32	T0D3	26.75	3.14	2.14 (2.09- 2.18)	0.25 (0.20- 0.30)	0.4914	23.48	24	0.9846
33	T0D3	26.63	2.42	2.13 (2.07- 2.18)	0.19 (0.12- 0.26)	0.6289	17.37	20	0.9675
34	T0D3	26.65	3.76	2.13 (2.08- 2.17)	0.30 (0.24- 0.36)	0.2007	28.41	23	0.9778
35	T0S8	25.96	3.69	2.09 (2.04- 2.14)	0.30 (0.24- 0.35)	0.2664	26.76	23	0.9825
36	T0S8	24.17	3.26	1.94 (1.89- 2.00)	0.26 (0.18- 0.34)	0.9852	10.79	23	0.9783
37	T0S8	23.31	4.24	1.87 (1.82- 1.93)	0.34 (0.25- 0.43)	0.8855	16.07	24	0.9663
38	T0S8	23.71	4.25	1.91 (1.85- 1.96)	0.34 (0.26- 0.42)	0.7351	18.41	23	0.9131
39	T0D6	24.81	5.09	2.01 (1.95- 2.08)	0.41 (0.32- 0.51)	0.1542	29.84	23	0.9142
40	T0D6	24.71	4.69	2.01 (1.95- 2.06)	0.38 (0.30- 0.47)	0.0035	45.41	23	0.9649
41	T0D6	25.13	3.88	2.04 (2.00- 2.08)	0.32 (0.26- 0.37)	0.1031	33.05	24	0.7546
42	T0S6	25.10	2.81	2.02 (1.98- 2.07)	0.23 (0.18- 0.27)	0.9930	9.06	22	0.9840
43	T0S6	25.95	4.65	2.09 (2.03- 2.15)	0.37 (0.29- 0.46)	0.1314	29.49	22	0.9392

Table 7: Results for combined model (5) with fixed and random effects using the method described in Fryer (1991) where D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the size selection process

		Multiplier	Value	SE	95% CI	*P*-value
SF	f_0	intercept	2.1575	0.0343	2.0893 – 2.2257	2.9273e-69
	f_1	td	-0.0247	6.8768e-3	-0.0384 − -0.0110	5.6158
	f_3	T90×td	-0.0412	4.0824e-3	-0.0493 − -0.0331	7.1936e-16
	f_5	T90×DO×td	-0.0253	5.417e-3	-0.0361 − -0.0145	1.2313e-5
SFA	g_1	td	0.0941	6.2664e-3	0.0816 – 0.1065	7.4037e-25
	g_2	td^2	-7.0250e-3	9.9873e-4	-0.0090 − -0.0050	6.4346e-10
	g_3	T90×td	-0.0163	3.048e-3	-0.0223 − -0.0102	8.7512e-7
Between	D_{11}	3.1507e-3				
Haul	D_{12}	3.1263e-4				
Variation	D_{22}	1.5233e-3				
Model	Log-likelihood				-246.78	
Statistics	AIC-value				563.55	
	Delta log-likelihood for the estimate				4.2050e-15	
	Number of hauls				43	

For visualization purposes, the predicted SF values were transformed to L50 values for the 120 mm nominal mesh size, as for cod. The increase in the L50 with increasing twine thickness is shown in Fig. 4 for the four different codend categories. The L50 tended to decrease monotonically for all four codend categories with a twine thickness in the range of 2 mm to 8 mm (Fig. 4).

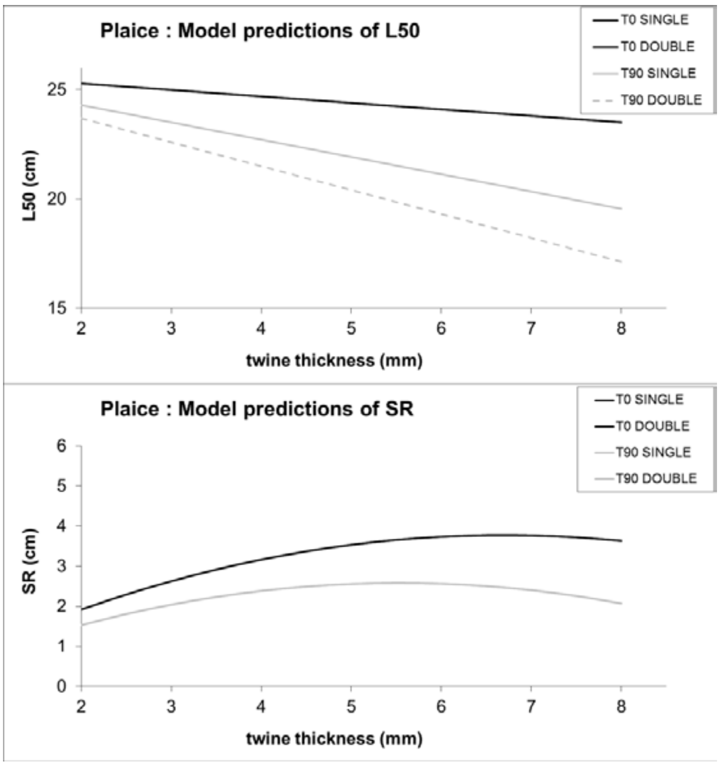

Figure 4: Predicted mean L50 and SR values for plaice, depending on the twine thickness. The SF and SFA values were rescaled to a 120-mm mesh size, according to the procedure described in section 2.2, for the different codend categories. The model-predicted L50 curves for T0 single and T0 double are identical. This also applies to both T0 and both T90 curves for the SR predictions.

For the SFA model (5) containing first order and second order terms for the effect of twine thickness (g1 and g2) with opposite signs, this relationship was more complex and it need to be inspected for specific values of twine thickness. However, turning the netting orientation to a T90 orientation tended to decrease the SFA and this effect increased with the twine thickness because g_3 was significantly less than zero (Table 7). Fig. 4 plots the predicted effect of the twine thickness on SR with a 120-mm codend mesh size.

Fig. 5 shows the rescaled (for a 120-mm mesh size) L50 and SR values for plaice in the individual hauls for the four different codend categories, which depended on the codend twine thickness. The CI for the individual haul parameters are shown, as well as the predicted between-haul variation in the selection process (see formula (2) and Table 7).

For all four codend categories, model (5) reproduced the main trends of the effect of twine thickness on the L50 and SR, which were found in the experimental results (Fig. 5). For plaice, none of the results for any of the 43 hauls were in direct conflict with the model for either the L50 and SR, after inspecting the CI of the estimated values in the individual hauls and the predicted between-haul variation in the selection process. This further supports our model selection procedure and basis model (section 2.2 and appendix). Thus, we can be confident when applying the model for plaice predictions.

Model (5) was used to predict the effect of an increase in the twine thickness on the mean value for L50 and SR with a 120-mm codend mesh size (Table 8). In addition, the percentage effect of turning the netting by 90° (from T0 to T90) was estimated for different twine thickness (see formulae 3, section 2.2).

In contrast to cod, the percentage effect of changing the netting orientation to T90 decreased with the increasing twine thickness for plaice. In addition, the effect was more profound for double twine netting compared with single twine netting. The effect with 2 mm twine was predicted to be -3.91% and -6.31% for single and double netting, respectively, but this effect increased to -16.83% and -27.15%, respectively, after increasing the twine thickness to 8 mm. For both T0 codend categories, increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 25.30 cm to 23.52 cm, which corresponded to a drop of 7%. The effect was more pronounced with T90 codends.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 8). This was based on the increase of the SR with thicker twine when applied in T0 codends. By contrast, the SR tended to be less dependent on the twine thickness with T90 codends.

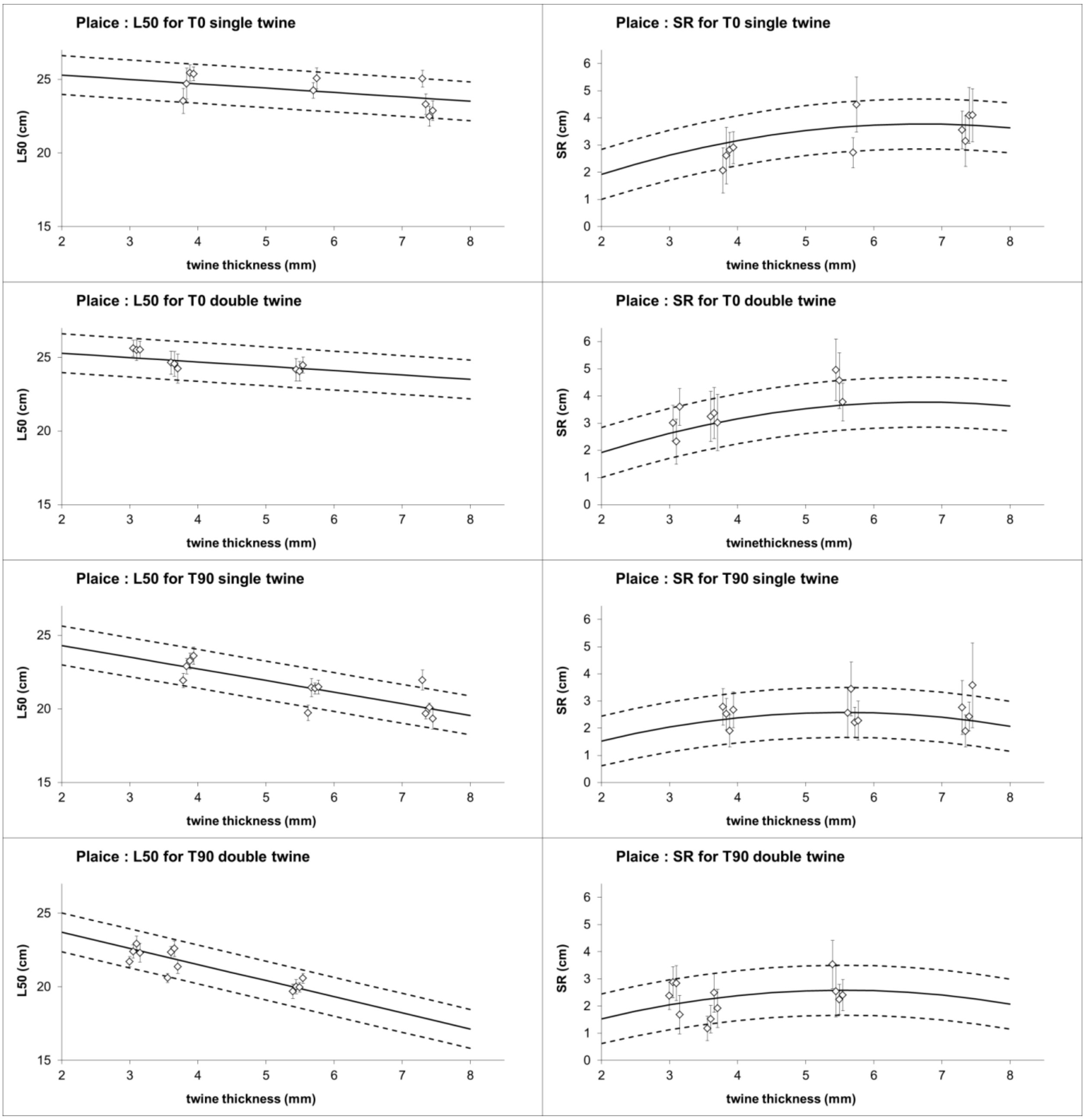

Figure 5: The L50 and SR values for plaice from single hauls using the four cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which were rescaled to a 120-mm mesh size.

Table 8: Model predictions for the influence of twine thickness on the size selection of plaice in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

	L50 Single Twine			L50 Double Twine			SR Single Twine			SR Double Twine		
td (mm)	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2	25.30 (24.76-25.83)	24.31 (23.70-24.92)	-3.91	25.30 (24.76-25.83)	23.70 (23.18-24.22)	-6.31	1.92 (1.61-2.23)	1.53 (1.18-1.88)	-20.33	1.92 (1.61-2.23)	1.53 (1.18-1.88)	-20.33
2.5	25.15 (24.68-25.62)	23.91 (23.33-24.50)	-4.92	25.15 (24.68-25.62)	23.15 (22.67-23.64)	-7.93	2.29 (1.89-2.70)	1.81 (1.36-2.25)	-21.26	2.29 (1.89-2.70)	1.81 (1.36-2.25)	-21.26
3	25.00 (24.58-25.42)	23.52 (22.94-24.09)	-5.93	25.00 (24.58-25.42)	22.61 (22.13-23.08)	-9.57	2.63 (2.13-3.12)	2.04 (1.50-2.58)	-22.28	2.63 (2.13-3.12)	2.04 (1.50-2.58)	-22.28
3.5	24.85 (24.48-25.22)	23.12 (22.54-23.70)	-6.97	24.85 (24.48-25.22)	22.06 (21.56-22.55)	-11.24	2.92 (2.32-3.52)	2.23 (1.58-2.89)	-23.42	2.92 (2.32-3.52)	2.23 (1.58-2.89)	-23.42
4	24.70 (24.36-25.04)	22.72 (22.12-23.33)	-8.01	24.70 (24.36-25.04)	21.51 (20.97-22.05)	-12.92	3.17 (2.46-3.88)	2.38 (1.62-3.15)	-24.67	3.17 (2.46-3.88)	2.38 (1.62-3.15)	-24.67
4.5	24.55 (24.23-24.88)	22.33 (21.69-22.97)	-9.06	24.55 (24.23-24.88)	20.96 (20.36-21.57)	-14.62	3.37 (2.54-4.20)	2.49 (1.60-3.38)	-26.06	3.37 (2.54-4.20)	2.49 (1.60-3.38)	-26.06
5	24.41 (24.07-24.74)	21.93 (21.25-22.62)	-10.13	24.41 (24.07-24.74)	20.42 (19.74-21.10)	-16.35	3.54 (2.58-4.49)	2.56 (1.54-3.58)	-27.61	3.54 (2.58-4.49)	2.56 (1.54-3.58)	-27.61
5.5	24.26 (23.90-24.62)	21.54 (20.80-22.28)	-11.21	24.26 (23.90-24.62)	19.87 (19.10-20.64)	-18.09	3.66 (2.56-4.75)	2.58 (1.42-3.75)	-29.36	3.66 (2.56-4.75)	2.58 (1.42-3.75)	-29.36
6	24.11 (23.71-24.51)	21.14 (20.34-21.95)	-12.31	24.11 (23.71-24.51)	19.32 (18.46-20.18)	-19.86	3.74 (2.50-4.98)	2.57 (1.25-3.88)	-31.35	3.74 (2.50-4.98)	2.57 (1.25-3.88)	-31.35
6.5	23.96 (23.50-24.42)	20.75 (19.87-21.62)	-13.42	23.96 (23.50-24.42)	18.77 (17.82-19.73)	-21.65	3.77 (2.37-5.18)	2.51 (1.03-3.98)	-33.63	3.77 (2.37-5.18)	2.51 (1.03-3.98)	-33.63
7	23.81 (23.30-24.33)	20.35 (19.40-21.30)	-14.54	23.81 (23.30-24.33)	18.23 (17.17-19.29)	-23.46	3.77 (2.20-5.34)	2.40 (0.75-4.05)	-36.26	3.77 (2.20-5.34)	2.40 (0.75-4.05)	-36.26
7.5	23.66 (23.08-24.25)	19.96 (18.93-20.98)	-15.67	23.66 (23.08-24.25)	17.68 (16.52-18.84)	-25.29	3.72 (1.97-5.47)	2.26 (0.43-4.09)	-39.34	3.72 (1.97-5.47)	2.26 (0.43-4.09)	-39.34
8	23.52 (22.86-24.17)	19.56 (18.45-20.67)	-16.83	23.52 (22.86-24.17)	17.13 (15.86-18.40)	-27.15	3.63 (1.69-5.57)	2.07 (0.05-4.10)	-42.99	3.63 (1.69-5.57)	2.07 (0.05-4.10)	-42.99

Discussion

This research addresses the effects of codend twine thickness and twine number on the size selectivity for round fish and flat fish species when using traditional T0 codends and T90 codends. This investigation is based on a case study of cod and plaice with experimental fishing in the Baltic Sea where both species are important for trawl fisheries (Probst et al., 2011). Based on an assumption that the fish morphology has a major role in the codend size selection process (Herrmann, et al., 2009; Frandsen et al., 2010; Krag et al., 2011; Herrmann et al., 2012), we expected that the trends in the results obtained for cod could be extrapolated to other round fish such as haddock due to similarities in their morphology (Sistiaga et al., 2011). Similarly, we expected that the trends in the results for plaice could be extrapolated to other flat fish species. This extrapolation relies on morphological similarities and it might be affected by differences in fish behavior.

For cod, the results for single and double twine T0 codends documented that the L50 decreased with increases in the twine thickness. This effect was more pronounced for double twine T0 codends. These results are in agreement with previously reported results for haddock (Lowry and Robertson, 1996; Kynoch et al., 1999; Herrmann and O'Neill, 2006; O'Neill and Herrmann, 2007) and they follow the same pattern as that observed in a Mediterranean study of other species (Sala et al., 2007). Our results for cod show that turning the netting orientation from T0 to T90, both for single and double twine netting, provided a significant increase in the L50 values and this effect increased with the twine thickness. These findings are logical when we consider the mechanical-based explanation given by Herrmann et al. (2007) to account for the effect of turning a diamond mesh netting by 90° (T90). For the double twine T90 codends, however, this positive effect was more than compensated for by the negative effect that an increase in the twine thickness had on the baseline T0 codend. Consequently, the L50 values decreased significantly with increasing twine thickness for double twine T90 codends. Thus, despite the positive effect of turning the netting, there was a decrease in the L50 values for cod with an increase in the twine thickness for double twined T90 codends.

In addition to the positive effect of increasing the twine thickness on the size selectivity with a T90 construction, this result highlights the importance of considering the other, and potentially counteracting, mechanisms described by Herrmann and O'Neill (2006). For the T90 single twine codends, our results indicate that these counteracting mechanisms can almost compensate for each other, resulting in only a slight decrease in the predicted L50 for cod with an increase in the twine thickness. Furthermore, the predicted decrease was not significant. Therefore, it cannot be ruled out that the counteracting mechanisms completely compensated for each other with this type of codend, resulting in a size selection process that did not depend on the twine thickness for cod. For cod, and potentially other round fish in general, the results obtained using double twine codends showed there was a significantly reduced size selection with T0 and T90 codend constructions. Therefore, improved size selectivity could be obtained by simply changing from double twine, which is the current commercial practice, to single twine codend netting. In general, our results demonstrated that using nets with a thinner twine in a single twine codend construction provided the highest L50 values. In the current experiments, the best results were obtained with a single twine T90 codend construction. Furthermore, the performance of this codend type appeared to be highly insensitive to the choice of twine thickness.

In addition to improved selectivity based on L50 estimates, the T90 constructions were predicted to allow a more acute size selection with smaller SR values. This appears to favor this type of codend for size selection with round fish. This effect may be because the meshes in the T90 codends are predicted to open more uniformly further ahead of where the catch accumulates compared with the T0 codends. The mesh opening was also less dependent on the size of the catch (Herrmann et al., 2007). One effect of a more uniform mesh opening could be a reduction in the SR in individual hauls (Herrmann, 2005b; Herrmann and O'Neill, 2005; Herrmann et al., 2009).

Initially, it was questioned whether the codend twine characteristics would affect the size selection of round fish and flat fish in the same direction and to the same extent. After we compared the results for cod and plaice, we concluded that there were some similarities but also major differences in the effects of the twine characteristics on size selection in both species. An increase in the twine thickness tended to decrease the L50 for cod and for plaice, whereas this effect was far less pronounced for plaice with T0 constructions. For example, we predicted that increasing the twine thickness from 2 mm to 8 mm for a single twine L50 would lead to decreases of 7% and 25% for plaice and cod, respectively. In contrast to cod, we found no evidence of any difference in performance between single and double twine T0 codends for plaice. Changing the netting orientation from T0 to T90 was predicted to affect the size selection for plaice in the opposite direction compared with cod. The percentage T90 effect for plaice significantly decreased with increasing twine thickness and the lowest values were obtained for the double twine T90 codend. It is possible that the differences in the effects on cod and plaice may be linked to differences in their morphology because the shape of plaice would require a diamond mesh with a relative small opening angle to pass though, whereas the shape of cod would benefit from a more open diamond mesh. This mechanism could potentially explain the different effects of increasing the twine thickness and turning the netting orientation

Our results were based on sea trials conducted using codends with a nominal mesh size of 120 mm. Thus, the results are most relevant to codend constructions with similar mesh sizes, which are used widely in North East Atlantic commercial fisheries. Based on the mechanisms described in Herrmann and O'Neill (2006) and Herrmann et al. (2007), we expect larger effects with smaller mesh sizes, because of the greater influence of a shorter mesh bar with increasing twine thickness. This mechanism also influences the T90-effect, so we also expect a larger T90 effect with smaller mesh sizes. By contrast, we would expect a very small T90 effect when using a relatively big mesh compared with the twine thickness and, therefore, the knot size in a T90 configuration. As a consequence, it may be possible to obtain stronger effects than the trends we observed based on the effects of the twine characteristics on codend size selection with smaller mesh sizes, and lower effects with bigger mesh sizes.

It is commercial practice in some fisheries to use different codend attachments such as chafers, round straps, or protective bags. The results presented here are based on codends with no such attachments. It is known that attachments such as round straps affect the codend shape (Herrmann et al., 2006) and devices that cover some of the codend meshes will affect the size selectivity of the codend (Kynoch et al., 2004). Consequently, these attachments might also influence the degree of the effects of the twine thickness and netting orientation.

We used the method described by Fryer (1991) to model size selection in the codends based on the effects of the codend netting design parameters (Table 1) and we assumed that the between-haul variation in the selection process could be modeled in a similar way for all of the codends we investigated. This is a usual approximation for this type of model, but it neglects potential differences in the between-haul characteristics of the different codends investigated (Wienbeck et al., 2011). However, to account for this would require far more hauls for each codend design. Additionally, the potential effect of codend catch weight on size selection (O'Neill and Kynoch, 1996 ;Herrmann, 2005b) is taken into account in model (1) by linear terms and by such approximated to affect the codend size selection independent of twine characteristics. This was omitted for SF and SFA in the resulting models (4) and (5) for cod and plaice, respectively. Thus, the results did not indicate any general trend in the effect of catch weight on the size selection of cod and plaice and we are confident in applying models (4) and (5) because a potential non-general effect of the codend catch weight is explicitly included in the between-haul variation modeling.

For the "T90 effect," it is important to note that our results are based on using new netting materials and we do not know if the effect of turning the codend netting orientation to T90 would disappear with the material relaxation caused by tension during fishing operations over some time (Herrmann et al., 2007). This would require a special experimental study to analyze any potential material-ageing effect.

The results presented in this study have some potential implications for fisheries management in different areas. The current legislation often permits the use of a relatively wide range of twine characteristics for codend constructions in many management areas. The current study showed that this has a potentially dramatic effect on the size selectivity of codends. Further, it is possible that the increasing trend to use thicker and double twined netting for T0 and T90 codends has created an artificial need for more sophisticated selective devices. These devices often include square mesh panels such as the BACOMA design (Madsen et al., 2002; Wienbeck et al., 2011) and other square mesh panel designs, such as those described by Madsen et al. (2010). The use of such constructions is often aimed at releasing juvenile round fish, such as cod. Based on the results obtained in the research reported here, we may question whether a simpler alternative could be used by some fisheries such as the deployment of diamond mesh codends (in T0 or T90 configuration) made of thinner single twine netting.

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Further material: Model development

In this section, we describe the development of the model that was used to quantify the effect of twine thickness in the netting used for codend construction on the size selection of a specific species. The model is a generic type and its parameter values were estimated by fitting the model to data from a species by species dataset. We also considered each submodel that could be derived by leaving out one or more parameters each time from the full-model (as described in section 2.2). The effect of the netting twine diameter on codend size selection was expected to differ with the different categories of codend category considered: $T0_{single}$, $T0_{double}$, $T90_{single}$, and $T90_{double}$ (Table 1). Therefore, we first developed a generic model for the effect of the twine diameter, which was applied separately to each codend category. In a second step, the resulting four models were aggregated into one. The size selection was described by the response parameters SF and SFA. Within a specific codend category (Table 1), we assumed that SF and SFA could be described using the continuous and differentiable functions *f* and *g* for the netting twine thickness *td*, as follows.

$$
\begin{aligned}
SF_i &= f_i(td) \\
SFA_i &= g_i(td) \\
\text{where } i &\in \{T0_{single}, T0_{double}, T90_{single}, T90_{double}\}
\end{aligned}
\qquad \text{(A1)}
$$

For the range of codend twine thicknesses handled by the resulting model, we assumed that *f* and *g* in (A1) could be approximated sufficiently accurately by using second order Taylor-expansions (see Bers and Karal (1976) for details on this kind of expansions) with *td* = 0.0 as the expansion point such that:

$$
\begin{aligned}
SF_i &\approx f_i(0.0) + \frac{\partial f_i(0.0)}{\partial td} \times td + \frac{1}{2} \times \frac{\partial^2 f_i(0.0)}{\partial td^2} \times td^2 \\
SFA_i &\approx g_i(0.0) + \frac{\partial g_i(0.0)}{\partial td} \times td + \frac{1}{2} \times \frac{\partial^2 g_i(0.0)}{\partial td^2} \times td^2
\end{aligned}
\qquad \text{(A2)}
$$

Therefore, we have four separate models with one for each codend category. We constrained the models to fulfill the asymptotic condition that the SF values should all progress toward the same value as *td* progress toward 0.0. We applied a similar asymptotic constrain on SFA. Thus, the *f(0.0)* and *g(0,0)* values become independent of the category, so the subscript *i* should be left out of these terms. The arguments for the asymptotic constraints are based on a mechanical point of view. The following argument was used: according to Herrmann et al. (2007), the knot size and the mesh bar bending stiffness potentially leads to differences in the SF and SFA values for the T0 and T90 codends made of the same netting material while the other design parameters remained identical. Based on simple geometrical consideration can it be expected that the knot size would increase approximately linearly with increase in twine diameter. Therefore, a gradual decrease in twine thickness towards zero should result in a gradual decrease in the knot size towards zero. A gradual degrease in the mesh bars bending stiffness towards zero with gradual degrease in twine thickness towards zero is also expected since this is well known from the thin beam theory where the bending stiffness is linearly dependent on the moment of inertia which in turn for a cylindrical cross section increases with the diameter in the power of 4 (Timoshenko and Goodier, 1982). According to beam theory will bending stiffness therefore progress towards zero as beam diameter progress towards zero. As a consequence of the above argumentation, a gradual decrease in twine thickness towards zero, should lead to a gradual decrease in the differences in the SF and SFA values for T0 and T90 codends towards zero. A similar type of argument can be applied to the asymptotic differences in the SF and SFA values for single or double twine codends, because their bending stiffness will affect the inner mesh aperture geometry, through which the fish try to attempt, which decreases with the twine thickness. Based on the above argument, it was assumed that a reasonably good approximation to set the *f(0.0)* and *g(0.0)* values in model (A2) as constants that are codend category independent. The validity to apply this approximation is further supported by the experimental size selectivity results for cod reported in ICES (2010). This source reports similar size selectivity for a T0 and a T90 codend made of the same thin (2.5 mm) single twine netting. Thus both L50 and SR and thus also SF and SFA were found to be very similar for the T0 and T90 codends and without statistical significant difference in values.

The next task was to find approximated relations between the $\frac{\partial f_i(0.0)}{\partial td}$ values in model (A2) and the other terms, which were still category dependent. This was the basis for aggregating the four category-specific models into a single model. The differences in the designs of the codends from different categories were defined based on the values of the two categorical design parameters: T90 (codend netting turn) and DO (netting with double twine) (Table 1).

It was assumed that the effects of the categorical parameters, T90 and DO, on the terms in model (A2) could be sufficiently well modeled separately using the functions q(T90, DO). The simplest form for *q(T90, DO)*, which was most likely to have the flexibility to model differences in the values of the terms in model (A2) between categories, would take the form:

$$q(T90, DO) = q_0 + q_1 \times T90 + q_2 \times DO + q_3 \times T90 \times DO \qquad \text{(A3)}$$

where q_0 is the intercept, which models the value for category $T0_{single}$. q_1 models the effect of changing the category from T0 to T90, while q_2 models the effect of changing from single to double twine (see Table 1). When applying both design changes (T0 to T90 and single twine to double), q_3 quantifies the interaction effect. It was assumed that this was sufficient to use models with the form model (A3) to model the relationships for the category-specific terms in model (A2). Using models with the form of model (A3) in model (A2) allowed us to formulate this using the following form when aggregating the different categories to model the effects of the category parameters T90 and DO.

$$SF = f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2$$

$$SFA = g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2$$

(A4)

Model (A4) was used to model the influence of the twine thickness on the SF and SFA for codends with different designs. Inspecting the form of model (A4) reveal the absence of twine thickness independent terms multiplied by respectively T90 and DO for SF and cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). This is a consequence of the asymptotic constrained argued for above in the model development. As described in section 2.2 was model (A4) and all submodels which could be derived from it by leaving of one or more terms at the time tested against each other. The model resulting in the lowest AIC value was then chosen to model the influence of twine characteristics on the size selection. To further inspect if the missing terms multiplied by respectively T90 and DO for SF and SFA would lead to any significant reduction in the ability to model the experimental data a second step in the model selection was applied were these two terms for both SF and SFA was added to the chosen model. Then as in the first model selection step this model and each simpler model which could be derived from it was tested against each other based on AIC values. If this second step results in selecting a model which is different from that of the first model selection step then the validity of applying the asymptotic constraint in the model selection need to be further critically evaluated.

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Annex 5:
Is it possible to simultaneously improve the size selection for round and flatfish species? The case of cod (Gadus morhua) and plaice (Pleuronectes platessa) in the Baltic Sea

Preface

The research presented here, was partly funded within this project. The analysis and writing was conducted in close cooperation between with Bent Herrmann (formerly DTU-Aqua, now SINTEF) after the time he left DTU-Aqua.

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Is it possible to simultaneously improve the size selection for round and flatfish species? The case of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) in the Baltic Sea

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Abstract

A range of different codend constructions and their effect on simultaneously improving the size selectivity of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) in the Baltic Sea trawl fisheries were investigated. The modifications included refining the selective performance of the current Bacoma codend by increasing the mesh size of the lower panel from 105 mm double twine to 130 mm single twine and increasing the mesh size in the upper (UltraCross) square mesh panel from 120 mm to 140 mm, and also making the lower panel of the same design as the upper panel; i.e. a full square mesh codend. These three experimental designs were tested in conjunction with the currently legislated codends; Bacoma 120 mm with 105 mm lower panel and T90 120 mm. Considering the current minimum landing sizes (MLS) for cod (38 cm) and plaice (25 cm) in the Baltic Sea and the fish population size structures during the sea trials, our results show that the T90 120 mm codend has the most favourable selection properties followed by the Bacoma codend with an increased lower panel mesh size of 130 mm.

Keywords: cod, plaice, codend selectivity, diamond mesh, square mesh, Bacoma, T90, SELNET, Baltic Sea

1. Introduction

The Baltic Sea demersal trawl fisheries are often classified as single species fisheries targeting cod (*Gadus morhua*). However, a considerable bycatch of flatfish species, namely plaice (*Pleuronectes platessa*), flounder (*Platichthys flesus*) and dab (*Limanda limanda*), can occur (ICES, 2011). The cod stocks in the Baltic Sea have seen a dramatic decline over the past 30 years, consequently various gear selectivity changes have been introduced in the Baltic Sea demersal fishery to reduce the capture of juvenile cod, and thus discard (Madsen, 2007; Suuronen and Sardà, 2007; Wienbeck et al., 2011). These technical regulations have focused on the selectivity of cod without considering important bycatch species such as plaice, flounder and dab.

Flatfish are mainly caught as bycatch in the cod directed trawl fishery and in a mixed flatfish trawl fishery, with landings of plaice being approximately 2000 tonnes annually (ICES, 2010). Discarding of plaice, flounder and dab within these fisheries is known to be high, with discard ratios (in weight) for these three species being 12-48 %, 33-60 % and 46-67 % respectively (Probst et al., 2011; Storr-Paulsen et al., 2012). Despite these species being highly discarded they are still of relative economic importance, with plaice and flounder being the second and third most important species (in value) within the Danish Baltic Sea demersal fisheries, respectively (The Danish AgriFish Agency, www.agrifish.dk). The high level of plaice discarded is not a result of a restrictive Total Allowable Catches (TAC) as these have not been fished in recent years (WKFLABA, 2010). Moreover, it is reported to be a problem of poor selectivity. Since the plaice abundance in the Baltic Sea has increased in recent years (ICES, 2011), improving plaice, and flatfish selectivity in the Baltic Sea is a growing issue.

In 2006, the T90 110 mm codend was introduced as an alternative to the Bacoma 110 mm codend for the Baltic Sea trawl fishery targeting cod (EU Regulation no. 2187/2005; Wienbeck et al., 2011). In 2010, the minimum mesh size of the Bacoma window and T90 codends was increased to 120 mm (EU Regulation no. 686/2010) and the length of the Bacoma window was extended from 3,5 to 6 m to prevent selectivity from decreasing at high catch rates (ICES, 2009; Madsen et al., 2010). The currently legislated Bacoma codend is made out of 105 mm (minimum mesh size) diamond meshes in the codend and 120 mm (minimum mesh size) single UltraCross square meshes in the window.

Cod selectivity has been widely studied in the Baltic Sea (Madsen, 2007) and the selectivity of the Bacoma and T90 codends have been optimised almost exclusively for cod while the selectivity of bycatch species, predominantly flatfish, has largely been ignored. Therefore, this study attempts to improve the size selection for cod and plaice simultaneously by analysing both currently legislated gears (Which one works best for both species?) and several trial codends (What are the effects on the size selectivity of cod and plaice) by modifying the total codend construction or only part of it, such as increasing the lower panel and window mesh size). In this study, we compared the size selectivity of the two currently legislated gears, Bacoma 120 mm (Bacoma SS120DD105; SS=single twine square mesh, SD=single twine diamond mesh, DD=double twine diamond mesh, followed sequentially by the nominal mesh size (mm) in the window and codend) and T90 120 mm (T90 SD120; where diamond mesh netting is turned 90 degrees), as well as three alternatives that could help improving the selectivity processes occurring in different parts of the codend. To improve the effectiveness of the Bacoma codend we i) increased the lower panel of the Bacoma codend from the currently legislated mesh size of 105 mm to 130 mm and also change from double to single twine in the lower panel (Bacoma SS120SD130), ii) increased the Bacoma window mesh size (upper panel) from the currently legislated 120 mm to 140 mm (Bacoma SS140DD105), and iii) constructed the entire codend out of UltraCross square mesh (SS120).

Increasing the mesh size in the lower panel has the potential to balance the difference in the selective performance of the upper and lower panel for roundfish like cod. Additionally, it may also improve the size selection of flatfish, since the currently legislated Bacoma codend (105 mm diamond mesh codend with a 120 mm escape window) is expected to perform relatively poorly compared to the MLS for plaice. Increasing the mesh size in the upper panel (Bacoma window) provides the possibility to quantify its effect on the total selectivity of the Bacoma codend. Constructing the entire codend out of UltraCross provided the possibility to quantify to which extent it matters for size selection of cod and plaice that the Bacoma window only covers the upper panel. If this is sufficient then in principle there should be no significant improvement in the size selection of cod by making the complete codend out of the UltraCross material. It also provides the possibility to investigate the size selective performance of square meshes for flatfish. Square meshes in the codend have previously been successfully used to improve the size selectivity of gadoids (Robertson and Stewart, 1988; Tschernij et al., 1996; Madsen et al., 1998; Madsen et al., 2002) whereas it has been indicated that the selectivity of flatfish is lower compared to diamond meshes (Walsh et al., 1989; Fonteyne and M'Rabet, 1992). It is likely that the morphology of flatfish makes it more difficult for them to penetrate square meshes than diamond meshes (Madsen et al., 2006).

Based on the above problem description, we test a range of different codend constructions (both square and diamond mesh configurations) and their effect on simultaneously improving the size selectivity of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) in the Baltic Sea trawl fisheries. In additions we quantified the benefits from applying the different codends in the specific fishery based on the values of a set of "codend usability indicators" which include the effect of the actual population size structures of the species investigated during the sea trials. These indicators therefore supplement the evaluation based on alone the size structure independent size selective properties of the different codends.

2. Material and Methods

2.1 Data collection

To investigate the research problem described in the introduction, we specifically tested 5 different codends: Bacoma SS120DD105, T90 SD120, Bacoma SS120SD130, Bacoma SS140DD105 and SS120 (Fig. 1)

FIG. 1

Mesh sizes in the codends were measured using an OMEGA-gauge with 125 N stretching force (Fonteyne et al., 2007; EU Regulation no. 517/2008). Table 1 summarizes the main data for the 5 codends.

TABLE 1

Each of the 5 codends was fished alternately, one at a time, while attached to the same trawl and the same extension piece. The trawl used was a "Codhopper," which has a circumference of 530 meshes and a 160 mm mesh size in the belly. The trawl was spread using two 3.5 m^2 Bison trawl doors. The extension piece for all codends was a T90 construction with 50 open meshes around and 50 meshes in length, made out of 120 mm single 'Polytit compact' netting with a twine thickness of 5 mm. The codend was the only change in gear between the individual tows. The covered codend method (Wileman et al., 1996) was applied. Supporting hoops and 4 kites were applied to keep the cover netting clear of the test codend. The 2.6 m diameter of the plastic cover hoop ensured that the cover's diamond shaped meshes (SD) were almost open like square meshes. The cover mesh size was 80 mm because previous experience during experimental fisheries in the same region and during the same season demonstrated that fishing with a smaller cover mesh size was impossible without a damage of the hoop during heaving because of the retention of large amounts of herring (*Clupea harengus*) and sprat (*Spratus spratus*) in the cover (Wienbeck et al., 2011). Compared with the recommendations of Wileman et al. (1996), this cover mesh size was rather large compared to the codend mesh sizes (Table 1). Therefore, special attention was given in the analysis to remove length classes where the selection of cover and codend potentially overlapped. The experimental fishing was conducted onboard the German Fishery Research Vessel (FRV) "Solea" (total length = 42 m, 950 kW, Sterntrawler). To make the conditions as similar as possible for each codend, all hauls were conducted on the same fishing ground.

2.2 Analysis of experimental size selection data

All individuals were measured to the nearest centimetre below their total length. No subsampling took place. Analysis of the two species was done separately and independently for each codend but using the same method. Hauls with at least 10 fish of the species of interest were included in the analysis. Taking into account the potential overlap between the size selection in the cover and the codend, all cod smaller than 33 cm were removed from the analysis (Wienbeck et al., 2011). The method of analysis is described below.

The experimental designs applied onboard Solea enabled analysis of the collected catch data as two-compartment data (binominal data; the fish were either retained by the cover (CC) over the codend or by the codend (C) itself to estimate the size selection in the codend (i.e., length-dependent retention probability). The two-compartment data format meant that for each haul (*j*) we had the number for fish of each length class *l* collected in compartment CC (nCC_{jl}) and in compartment C (nC_{jl}), respectively. The probability of finding a fish with length *l* in compartment C in haul *j* given that it is found in one of the compartments is expressed by the function $r_j(l)$. The purpose of the analysis is to estimate the values of this function for all relevant sizes of cod and plaice. Between hauls with the same codend the value of $r_j(l)$ is expected to vary (Fryer, 1991). In this study we have no specific interest in this between-haul variation, instead, we were interested in the length-dependent values of $r(l)$ averaged over hauls because this would provide information about the average consequences for the size selection process of applying the different codends in the fishery. Thus, we assumed that the size selective performance of a specific codend for the group of hauls conducted was representative of how the codend would perform in a commercial fishery (Millar, 1993; Sistiaga et al., 2010).

Estimation of the average size selection over hauls $r_{av}(l)$ involves pooling data from the different hauls with this codend (without any raising of data since no subsampling was applied in the data collection). According to Fryer (1991), simply pooling data over hauls could lead to underestimation of the uncertainties in the size selection process due to the potential between-haul variation. This problem was resolved by using a double bootstrapping technique that accounts for both within- and between-haul variation in the selection process. For each case analyzed (specific species for specific codends), 10000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Efron, 1982; Chernick, 2007). Because this technique is similar to the one applied by Sistiaga et al. (2010), Eigaard et al. (2011), Herrmann et al. (2012), and Madsen et al. (2012), it is not described further here. Since we tested different parametric models for $r_{av}(l)$, we write $r_{av}(l,\boldsymbol{v})$, where $\boldsymbol{v}$ is a vector consisting of the parameters of the model. The purpose of the analysis is to estimate the values of the parameter $\boldsymbol{v}$ that make experimental data (averaged over hauls) most likely to be observed, assuming that the model is able to describe the data sufficiently well. Thus, function (1) was minimized, which is equivalent to maximizing the likelihood for the observed data:

$$\sum_j \sum_l \left\{ nC_{jl} \times ln\left(r_{av}(l,\boldsymbol{v})\right) + nCC_{jl} \times ln\left(1.0 - r_{av}(l,\boldsymbol{v})\right)\right\} \qquad (1)$$

where the summations are over hauls *j* for one specific codend type and length classes *l*.

Four different models were tested as candidates to describe $r_{av}(l,\boldsymbol{v})$ for each codend and species individually: Logit, Probit, Gompertz and Richard. The formulas for these models and the calculation of the selection parameters, L50 and SR, are described below; formulas (2)-(5). Further details on these size selection models can be found in Wileman et al. (1996).

Logit :

$$r_{av}(l,\boldsymbol{v}) = \frac{exp(v_1 + v_2 \times l)}{1 + exp(v_1 + v_2 \times l)}$$
$$L50 = -\frac{v_1}{v_2} \qquad (2)$$
$$SR = \frac{ln(9)}{v_2}$$

Probit (cummulative normal distribution Φ):

$$r_{av}(l,\boldsymbol{v}) = \phi(v_1 + v_2 \times l)$$
$$L50 = -\frac{v_1}{v_2} \qquad (3)$$
$$SR = \frac{2 \times \phi(0.75)}{v_2}$$

Gompertz:

$$r_{av}(l, \boldsymbol{v}) = exp\left(-exp(-v_1 - v_2 \times l)\right)$$
$$L50 = -\frac{ln\left(-ln(0.5)\right) + v_1}{v_2} \qquad (4)$$
$$SR = \frac{ln\left(\frac{ln(0.25)}{ln(0.75)}\right)}{v_2}$$

Richard:

$$r_{av}(l, \boldsymbol{v}) = \left(\frac{exp(v_1 + v_2 \times l)}{1 + exp(v_1 + v_2 \times l)}\right)^{\frac{1}{v_3}}$$
$$L50 = \frac{logit(0.5^{v_3})}{v_2} \qquad (5)$$
$$SR = \frac{logit(0.75^{v_3}) - logit(0.25^{v_3})}{v_2}$$
$$D = \frac{1}{v_3}$$

Evaluating the ability of a model to describe the data sufficiently well using (1) is based on calculating the corresponding p-value, which expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this p-value should not be below 0.05 (Wileman et al, 1996). Model deviance versus degree of freedom also can be applied in the model evaluation (Wileman et al., 1996). Selection of the best model among those with acceptable p-values is based on comparing the AIC values for the models. The selected model is the one with the lowest AIC value (Akaike, 1974).

Size selectivity was analyzed using the software SELNET following the methodological recommendations in Wileman et al. (1996). SELNET offers a variety of additional models and methods for analysis, including the double bootstrap technique described above. SELNET was developed by the second author of the study reported here, and additional information about the software can be obtained from him or by consulting Sistiaga et al. (2010), Eigaard et al. (2011), Frandsen et al. (2011), Wienbeck et al. (2011), Madsen et al. (2012), and Herrmann et al. (2012).

The inspection of length classes with a lack of overlap between the 95% confidence limits was carried out to determine whether there were any significant differences between the different codends. Therefore, selection curves for the different codends were plotted pairwise, with confidence limits.

For the size selective properties of a codend to be well fitted with the MLS values in place for the specific fishery ideally the codend retention probabilities for all sizes below MLS's should be low and for all size above the MLS's the retention probabilities should be high. We will use these criteria's to judge the size selective properties of the different codends in relation to the usability for the specific fishery. To somehow also account for the population size structures of the species abundant in the fishery we will supplement this evaluation by also using indicators which contrary to the size selective properties of the codend also consider the effect of the population size structures of the species available in the specific fishery. These indicators are defined in the following section.

2.3 Estimation of codend usability indicators

To assist evaluation of the usability of the five different codends against each other for the specific fishery the value of four different indicators were estimated for both cod and plaice individually. Contrary to the size selection properties, which provide information that are independent of the size structure of the population of the fish species in the specific fishery where the codends are tested, are the values of the indicators defined in this section directly dependent on the size structure of the fish species in the specific fishery. Thus these indicators supplement the evaluation based on size selective properties with properties which are directly dependent on the population size structures in the specific fishery. Therefore the values of these indicators quantify the usability of the specific codends while accounting for the population size structures abundant during the sea trials. The following indicators are used:

$$
\begin{aligned}
nP_{-} &= 100 \times \frac{\sum_j \{\sum_{l<MLS} nc_{jl}\}}{\sum_j \{\sum_{l<MLS} \{nc_{jl} + ncc_{jl}\}\}} \\
nP_{+} &= 100 \times \frac{\sum_j \{\sum_{l>MLS} nc_{jl}\}}{\sum_j \{\sum_{l>MLS} \{nc_{jl} + ncc_{jl}\}\}} \\
nRatio\pm &= \frac{\sum_j \{\sum_{l<MLS} nc_{jl}\}}{\sum_j \{\sum_{l>MLS} nc_{jl}\}} \\
dnRatio &= 100 \times \frac{\sum_j \{\sum_{l<MLS} nc_{jl}\}}{\sum_j \{\sum_{l} \{nc_{jl}\}\}}
\end{aligned}
\qquad (6)
$$

where the summation *j* is over hauls with a specific codend. The summation *l* is over length classes. The four different indicators are each described below:

nP₋ gives a quick estimate of how large a fraction of the number of individuals below MLS a specific codend catch. It thus gives an indication of if fishing with a specific codend on the population structure of the species available where the fishing is conducted is a problem. nP_{-} should preferable be low.

nP_{+} gives an indication on the retention efficiency of the population above MLS for the specific codend while considering the size structure of the population fished on. If the species is a target species it is preferable that nP_{+} is high (close to 100).

nRatio± gives the number of individuals below MLS retained per individual above MLS retained. Thus for the size selectivity for the codend to be well adjusted for the MLS and considering the population size structure fished on *nRatio±* should be low (close to zero).

dnRatio gives the species specific percentage discard ratio based on number of fish assuming that every fish above MLS is kept by the fisherman. The lower *dnRatio* is the better is the codend suited for the specific fishery.

To estimate the uncertainty in nP_{-}, nP_{+}, *nRatio±* and *dRatio* for each species, considering both the effect of between-haul variation and uncertainty related to within-haul variation, we used the double bootstrapping method described above to estimate the "Efron percentile" 95 confidence limits for the estimated indicator values. The analysis was conducted using the software tool SELNET, described in the previous section.

3. Results

3.1 Haul information and catch data

The experimental fishing trials were carried out over a period of 19 days (8th - 26th September 2011) in the Arkona Basin, western Baltic Sea. The water depth varied between 32 and 64 m on the fishing grounds. The average towing speed was 3.6 knots, with a range of 3.4–3.8 knots. The haul duration was between 114 and 210 min (mean = 170 min). The size selectivity data for cod and plaice were collected from a total of 43 valid hauls (Table 2). In addition to cod and plaice, flounder were abundant in the codend while large quantities of herring and sprat were retained in the cover.

3.1 Results for Cod

A total of 33200 cod, larger than 33 cm, were included in the analysis. The number of cod (>33 cm) in the different test codends ranged from 1185 to 2918 individuals, and from 3139 to 5502 in the covers. Cod data from 8, 8, 8, 9 and 10 hauls were included in the analysis of the Bacoma SS120DD105, T90 SD120, Bacoma SS120SD130, Bacoma SS140DD105 and SS120 codends, respectively. The catch data for cod is summarized in Table 2.

TABLE 2

The four different selection models (section 2.2) were tested on the size selection data for cod for each of the 5 codends. Model selections were based on obtained AIC-values and summarized in Table 3.

TABLE 3

Using the selected models for each codend, size selectivity estimates were calculated (Table 4) and the resulting curves together with their 95% confidence intervals are shown (Fig.2). Inspecting the p-values and deviance versus DOF from the fit statistics (Table 4) revealed that the experimental data are described sufficiently well by the models. The size selection, and therefore the retained fraction of cod and plaice, varied between investigated codends (Fig. 2 and Fig. 3).

TABLE 4

FIG. 2

Fig. 3 plots the CI for the selection curves for the different codends pairwise.

FIG. 3

Of the two currently legislated gears the T90 SD120 codend had a significantly larger L50 and a smaller SR for cod compared to the Bacoma SS120DD105 codend (Table 4). The T90 SD120 codend also had the lowest percentage retention of undersized cod, the lowest number of undersized cod caught per well sized cod caught and the lowest discard ratio (nP_{-}, *nRatio±* and *dnRatio* in Table 4). The largest L50 for cod was observed for the full UltraCross codend (SS120). The significant increase in size selectivity for the full UltraCross codend compared to the legislated Bacoma SS120DD105 codend (Fig. 3D) means that a large number of individuals are unable to successfully utilise the Bacoma window. The full UltraCross also had the lowest percentage retention of individuals above MLS (32%; nP_{+} in Table 4). The loss of legal sized individuals directly translates into an increase in effort and therefore an additional catch of undersized cod. This is quantified in both the number of undersized cod caught per well sized caught and in the discard ration (*nRatio±* and *dnRatio* in Table 4). Increasing the mesh size of the lower panel in the Bacoma codend (Bacoma SS120SD130) increased the L50 and SR compared to the legislated Bacoma, however, not significantly (Table 4). Increasing the mesh size in the Bacoma window (Bacoma SS140DD105) significantly increased the L50 for cod compared to the legislated Bacoma codend (Bacoma SS120DD105). Increasing the mesh size in the Bacoma window also resulted in a significant reduction in the percentage of cod ≥MLS retained compared to the legislated Bacoma codend (nP_+ in Table 4). No significant change in the size selectivity of cod occurred compared to the legislated Bacoma codend when increasing the mesh size in the lower panel since an overlap between the confidence limits for the selection curves was present for all length classes (Fig. 3B). However, when increasing the mesh size of the upper panel a significant change in size selectivity can be observed both below and above MLS (Figure 3C).

3.2 Results for Plaice

A total of 5363 plaice were included in the analysis. The number of plaice in the different test codends ranged from 108 to 1994 individuals and from 8 to 1307 in the cover. Plaice data from 5, 6, 9, 8 and 10 hauls were included in the analysis of the Bacoma SS120DD105, T90 SD120, Bacoma SS120DD130, Bacoma SS140DD105 and SS120 codends, respectively. The catch data for plaice is summarized in Table 5.

TABLE 5

The four different selection models (section 2.2) were tested on the size selection data for plaice for each of the 5 codends. Model selections were based on obtained AIC-values and summarized in Table 6.

TABLE 6

Using the selected models for each codend, the selectivity estimates are calculated (Table 7) and the resulting curves and 95% confidence limits are shown (Figure 4). Inspecting the *p*-values and deviance versus DOF from the fit statistics (Table 7) revealed that the experimental data are described sufficiently well by the selected models.

TABLE 7

FIG. 4

Fig. 5 plots the CI for the selection curves for the different codends pairwise.

FIG. 5

The T90 120 mm (T90 SD120) codend has a significantly higher L50 for plaice compared to the currently legislated Bacoma codend (Bacoma SS120DD105; Table 7), while the SRs is quite similar. Increasing the mesh size in both, the lower (Bacoma SS120SD130) and the upper (Bacoma SS140DD105), panels of the Bacoma codend resulted in significant increases in the L50 for plaice; while the full UltraCross codend (SS120) resulted in the lowest L50 (Table 7). The T90 SD120 codend had the lowest percentage retention of undersized plaice (26.3 %; nP_{-} in Table 7) while still retaining more than 90 % of the legal sized plaice (nP_{+} in Table 7). This codend also had the lowest ratio of undersized plaice caught per well sized caught and the lowest discard ratio (*nRatio±* and *dnRatio* in Table 7) .Increasing the mesh size in both the lower (Bacoma SS120SD130) and upper (Bacoma SS140DD105) panel of the Bacoma codend also resulted in significantly lower retention of undersized plaice, however, significant reductions of legal sized plaice also occurred (nP_{-} and nP_{+} in Table 7). The currently legislated Bacoma SS120DD105 and the full UltraCross (SS120) codends retained more than 80 % of undersized plaice (nP_{-} in Table 7). The T90 SD120 codend and both modified Bacoma codends (Bacoma SS120SD130 and Bacoma SS140DD105) significantly improved the size selection of plaice (Fig. 5A, B, C). The two codends which performed best were the T90 SD120 and the Bacoma SS120SD130 codends, with the T90 SD120 codend retaining significantly more legal sized plaice (Fig. 5E, Table 7). The T90 SD120 codend and both modified Bacoma codends (Bacoma SS120SD130 and Bacoma SS140DD105) performed significantly better than the full UltraCross codend (SS120) (Fig. 5G, I, J).

Discussion

To simultaneously improve the size selectivity of round and flatfish species can be difficult due to large differences in their morphological characteristics. The mismatch between the selectivity of the codends and the MLS for plaice is rather large for all codends (Fig. 4f) compared to the selectivity for cod.

The codends which had the best size selection of cod and plaice simultaneously were the T90 SD120 codend and the Bacoma codend with a larger mesh size and single twine in the bottom panel (Bacoma SS120SD130). Both of these codends had a low retention of cod and plaice under MLS. Especially, the shape of the meshes in the T90 SD120 codend appears to suit the morphological characteristics of both round and flatfish relatively well. This is could be potentially due to the meshes remaining more open than the traditional diamond meshes, allowing for greater selectivity of both species

The Bacoma SS120SD130 codend with the larger mesh size in the bottom panel had a significantly lower retention of larger plaice than the two legislated codends. Lowering the retention of legal sized plaice may be desirable in months when the quality, and subsequently the price, is lower. For example, it has been observed that discarding of plaice ≥MLS is higher during the winter months (Feekings et al., 2012) and can be attributed to the physical condition of plaice during the period being lower, resulting also in lower market value (Poos et al., 2010). Therefore, lowering the retention of small and large plaice during the winter months when they are of poor physical condition may be beneficial in reducing the number of plaice discarded.

The differences in selectivity for cod and plaice observed across codends demonstrate the possibility for fishermen to modify their gears in order optimize their usage of fishing quota, especially in the light of upcoming changes in European fisheries management. For example, when the quota for flatfish species is close to being fished up, fishermen may have the possibility to either shift from the legislated Bacoma codend to the T90 SD120 codend or a Bacoma codend with an increased mesh size in the lower panel (Bacoma SS120SD130). It is expected that the presented findings are also relevant for mixed demersal fisheries in other areas (e.g. North Sea).

The significantly lower retention of cod in the full UltraCross codend (SS120) compared to the legislated Bacoma SS120SD105 codend can be interpreted as not all individuals being able to successfully contact and escape through the Bacoma window. Furthermore, the full UltraCross condend retained a high proportion of small flatfish, which is in correspondence with previous results (Walsh et al., 1989).

As expected, increasing the mesh size in the Bacoma window resulted in a significantly lower retention of cod across almost all sizes. The retention of legal sized cod almost halved compared to the currently legislated Bacoma codend (Table 4). Again, this can be translated into a necessary increase in effort to fish the quota available.

It could be speculated that cod mainly tries to escape through the upper panel and most flatfish escapement attempts directed to the lower panel. Nevertheless, increasing the upper and lower panels in the Bacoma codend resulted in a significant increase in the selectivity of plaice. Therefore, plaice, and possibly other flatfish species, have the potential to contact both, the upper and lower panels. However, the panels tested here extended all the way to the aft end of the codend, which might increase the possibility for individuals to come in contact with the upper panel directly in front of the aggregated catch. This finding might therefore only hold true for such cases. Further study needs to be carried out which look into the effect of window placement.

Of the two currently legislated gears, the T90 SD120 codend performs better for plaice and cod; retaining significantly less undersized individuals of both species while still having a high retention of legal sized plaice. The retention of legal sized cod was lower for the T90 SD120 codend but not significantly different. A decrease in the retention of legal sized individuals equated to an increase in effort which is needed to catch the quota. From an environmental and economic perspective, such an increase in effort is undesirable and might result in even higher absolute discards. The results for the T90 SD120 are obtained for a codend constructed using single twine with a nominal twine thickness of 4 mm. The current legislation permits also use of thicker twine and double twine. It is currently unknown in what direction and to what extent the use of different twine thicknesses and the use of double twine netting would affect the results obtained for the T90 SD120 codend. Thus we must warn that the comparison made for the T90 SD120 codend in this study is only valid for 4 mm single twine. Additionally, the comparison made between the fractions of fish retained below and above MLS (nP_- , nP_+) is specific to the size structure of the population fished during the experimental fishing trials.

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Fig. 1: Photos of the five different codends used in this study. Pictures are taking while codends were hanging from a crane. From left to right: BACOMA SS120DD105, T90 SD120, BACOMA SS120SD130, BACOMA SS140DD105, and UltraCross SS120.

Fig. 2: Size selection of cod in the five different codends. The first 5 panels (A-E) show results for the different codends separately where: Diamond symbols represent the experimental data; Thick black curve indicate the fitted size selection curves; Stipple curves describe the 95% confidence limits for the fitted size selection curves; Vertical stipple line represent the MLS for cod; Thin dotted curves represent the population of cod entering the

codend; Grey curves show the population of cod retained in the codends. The last panel (F) compares the mean size selection curves for each codend.

Fig. 3: Each panel compares the 95% confidence limits for the estimated size selection curves for cod, pairwise. The grey curves represent the confidence limits for the first codend mentioned in the panel legend while the black curves represent the confidence limits for the second codend mentioned in panel legend. For example, in the first panel (A) the grey curves represent the BACOMA SS120DD105 codend and the black curves the T90 SD120 codend. The vertical line shown in each panel represents the MLS for cod.

Fig. 4: Size selection of plaice in the five different codends. The first 5 panels (A-E) show results for the different codends separately where: Diamond symbols represent the experimental data; Thick black curves indicate the fitted size selection curves; Stipple curves describe the 95% confidence limits for the fitted size selection curves; Vertical stipple lines represent the MLS for plaice; Thin dotted curves represent the population of plaice entering each codend; Grey curves show the population of plaice retained in the codends. The last panel (F) compares the mean size selection curves for each codend.

Fig. 5: Each panel compares the 95% confidence limits for the estimated size selection curves for plaice, pairwise. The grey curves represent the confidence limits for the first codend mentioned in the panel legend while the black curves represent the confidence limits for the second codend mentioned in panel legend. For example, in the first panel (A) the grey curves represent the BACOMA SS120DD105 codend and the black curves the T90 SD120 codend. The vertical line shown in each panel represents the MLS for plaice.

Fig. 1

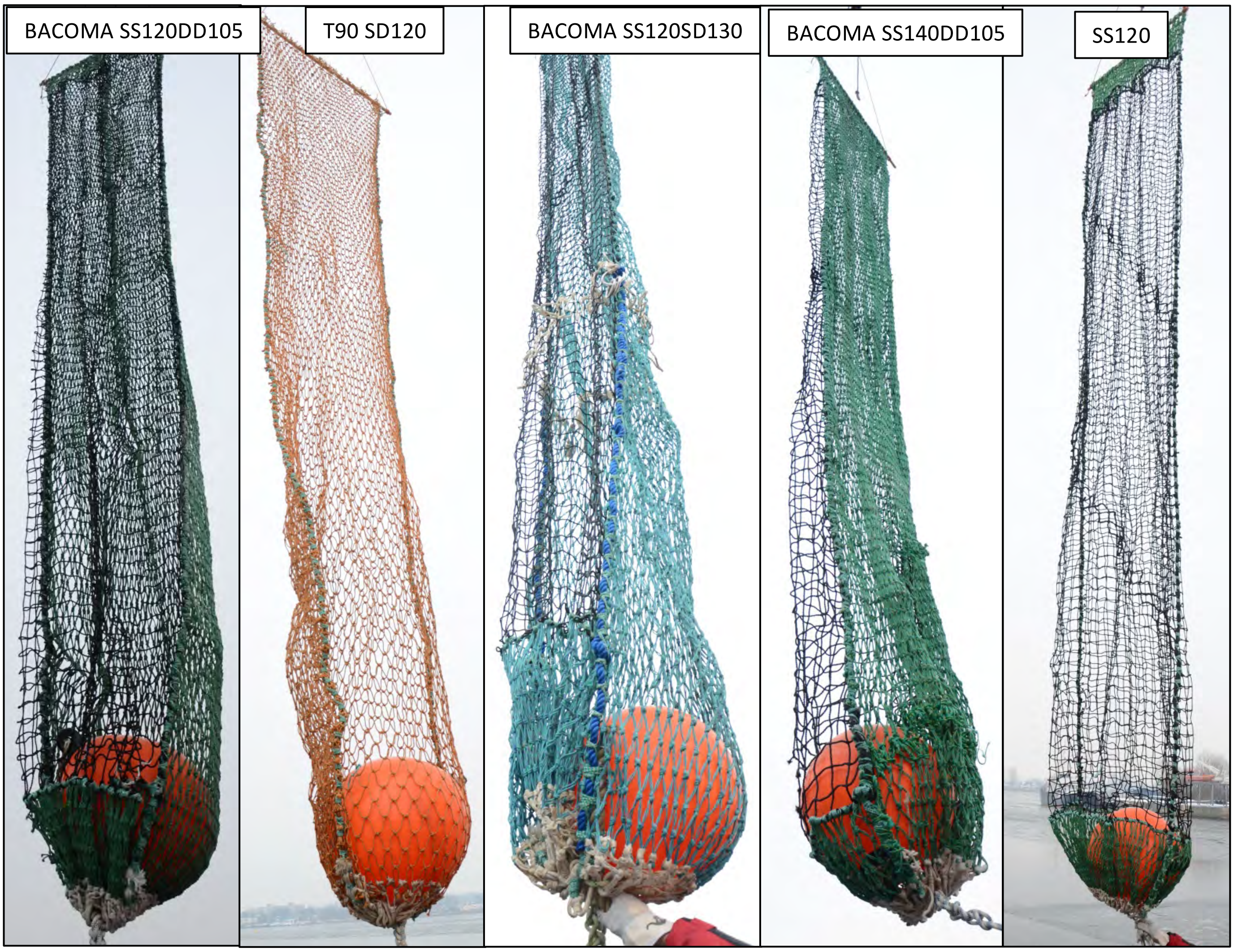

BACOMA SS120DD105
T90 SD120
BACOMA SS120SD130
BACOMA SS140DD105
SS120

Fig. 2.

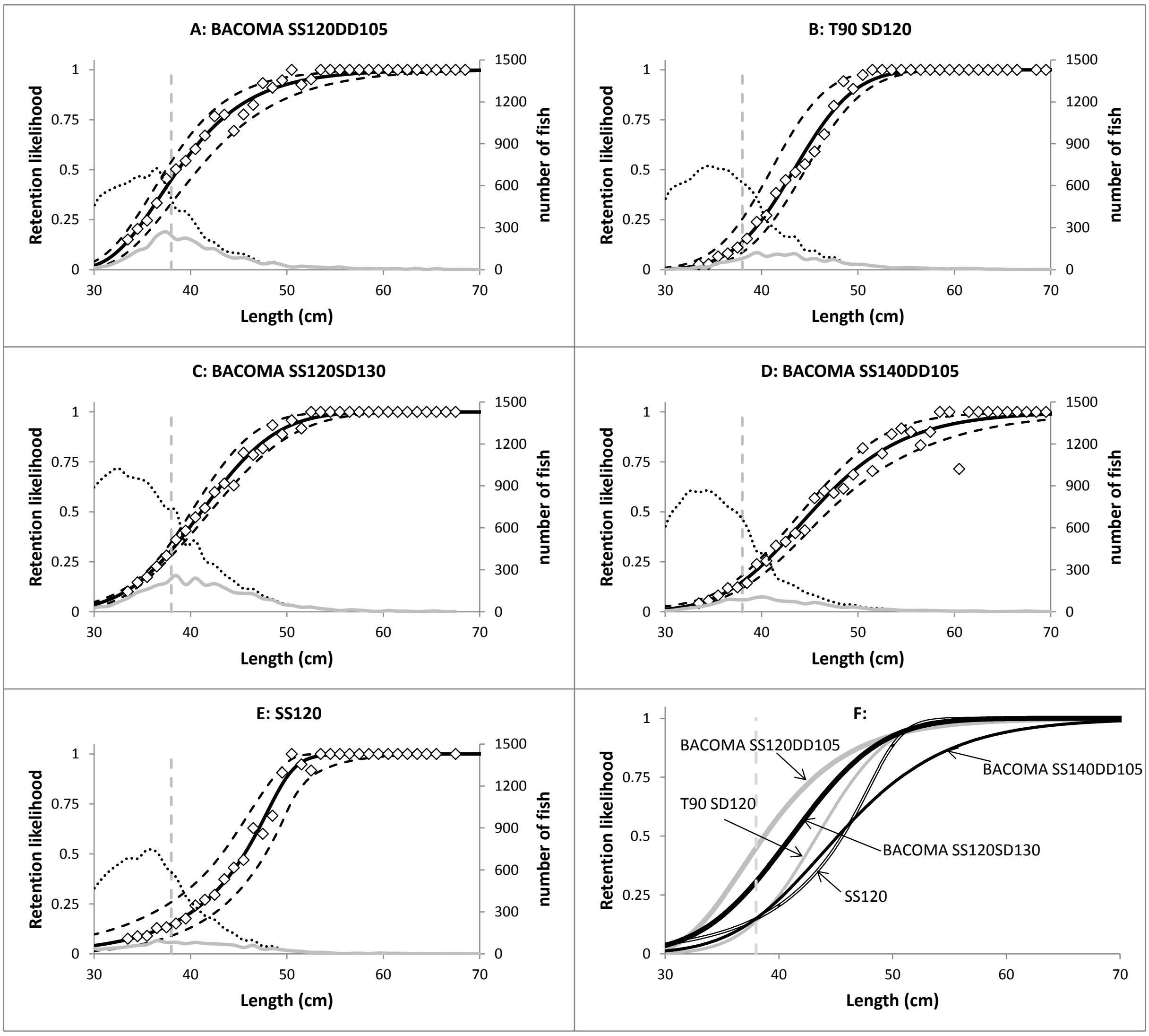

A: BACOMA SS120DD105
B: T90 SD120
C: BACOMA SS120SD130
D: BACOMA SS140DD105
E: SS120
F:
Retention likelihood
number of fish
Length (cm)
BACOMA SS120DD105
T90 SD120
BACOMA SS120SD130
SS120
BACOMA SS140DD105

Fig. 3.

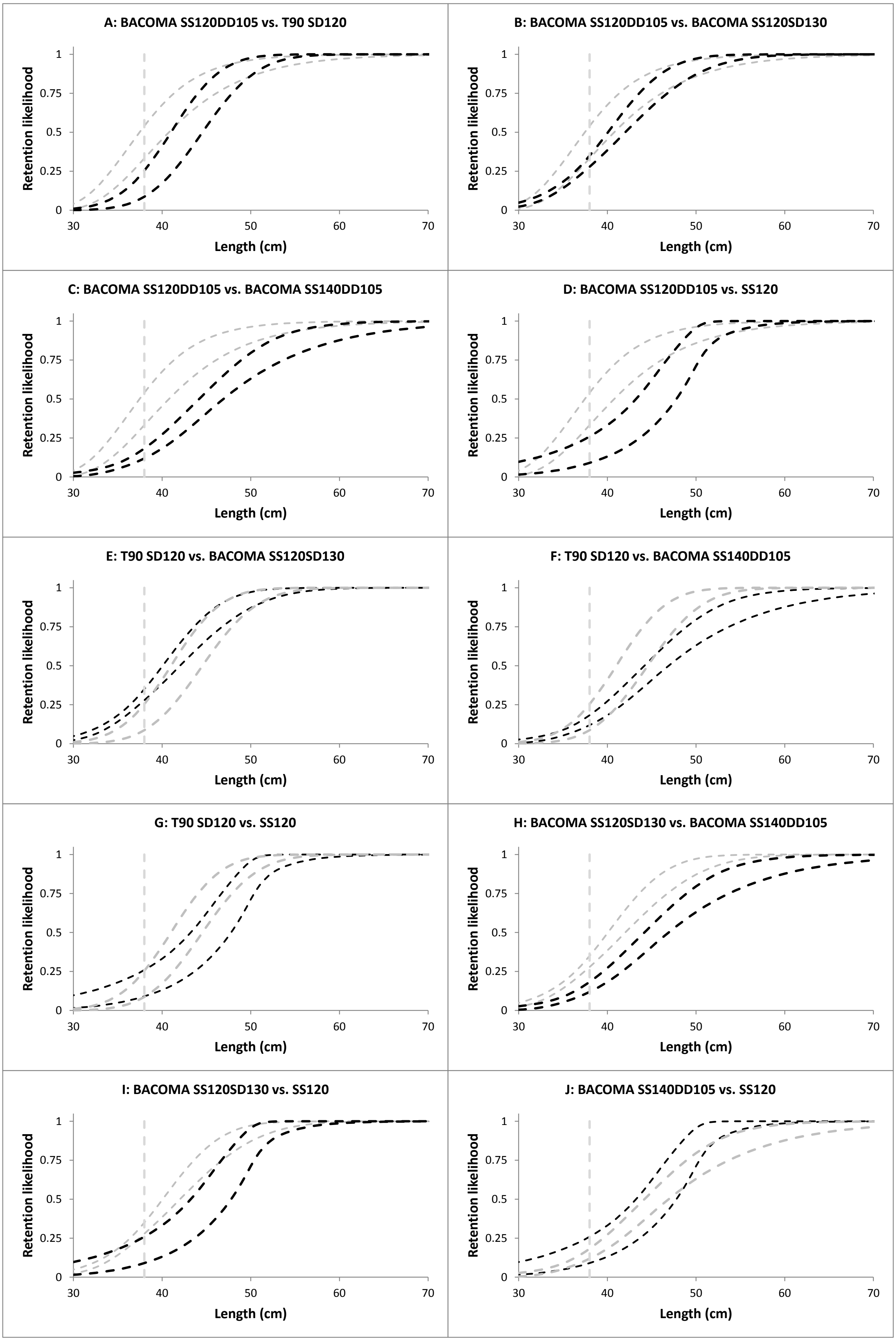
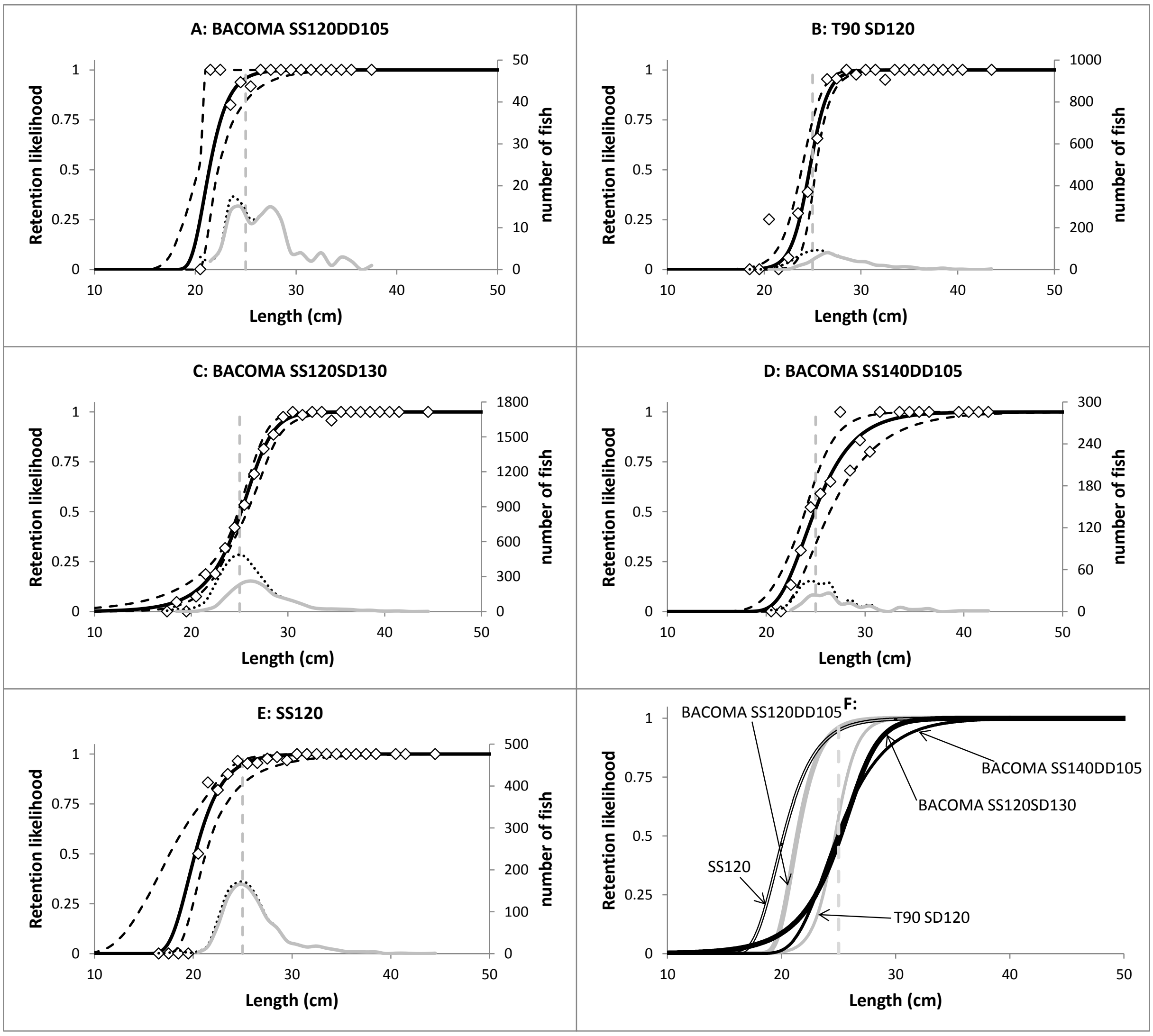

A: BACOMA SS120DD105 vs. T90 SD120
B: BACOMA SS120DD105 vs. BACOMA SS120SD130
C: BACOMA SS120DD105 vs. BACOMA SS140DD105
D: BACOMA SS120DD105 vs. SS120
E: T90 SD120 vs. BACOMA SS120SD130
F: T90 SD120 vs. BACOMA SS140DD105
G: T90 SD120 vs. SS120
H: BACOMA SS120SD130 vs. BACOMA SS140DD105
I: BACOMA SS120SD130 vs. SS120
J: BACOMA SS140DD105 vs. SS120
Retention likelihood
Length (cm)
0
0.25
0.5
0.75
1
30
40
50
60
70

Fig. 4



A: BACOMA SS120DD105
B: T90 SD120
C: BACOMA SS120SD130
D: BACOMA SS140DD105
E: SS120
F:
Retention likelihood
number of fish
Length (cm)
BACOMA SS120DD105
BACOMA SS140DD105
BACOMA SS120SD130
SS120
T90 SD120

Fig. 5

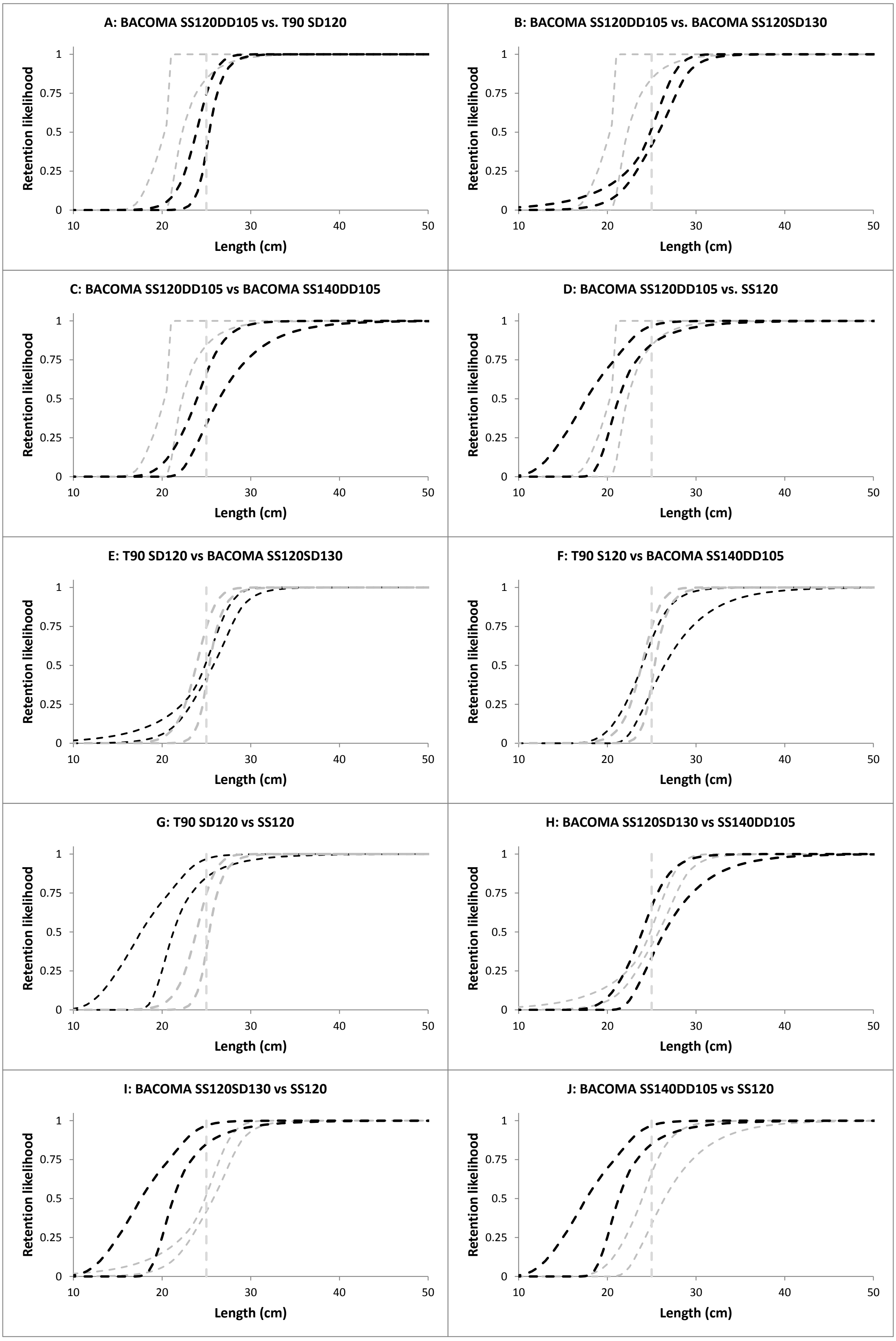

A: BACOMA SS120DD105 vs. T90 SD120
B: BACOMA SS120DD105 vs. BACOMA SS120SD130
C: BACOMA SS120DD105 vs BACOMA SS140DD105
D: BACOMA SS120DD105 vs. SS120
E: T90 SD120 vs BACOMA SS120SD130
F: T90 S120 vs BACOMA SS140DD105
G: T90 SD120 vs SS120
H: BACOMA SS120SD130 vs SS140DD105
I: BACOMA SS120SD130 vs SS120
J: BACOMA SS140DD105 vs SS120
Retention likelihood
Length (cm)
0
0.25
0.5
0.75
1
10
20
30
40
50

TABLE 1: Specification of the codends. *: number of bars wide. Mesh sizes are measured with an Omega gauge with 125 N.

		BACOMA SS120DD105	T90 SD120	BACOMA SS120SD130	BACOMA SS140DD105	SS120
upper	mesh size	132.3	126.2	130.0	146.7	127.9
panel	mesh type	square	T90	square	square	square
	twine diameter	single 5 mm	single 4 mm	single 5 mm	single 7 mm	single 5 mm
	material	UltraCross	Polytit compact PE	UltraCross	UltraCross	UltraCross
	number meshes wide	25*	25	23*	21*	25*
lower	mesh size	109.8	126.1	129.4	110.8	129.8
panel	mesh type	diamond	T90	diamond	diamond	square
	twine diameter	double 4 mm	single 4 mm	single 4 mm	double 4 mm	single 5 mm
	material	Euroline PE	Polytit compact PE	Alfa compact PE	Euroline PE	UltraCross
	number meshes wide	50	25	40	50	25*

TABLE 2: Summary of hauls used for the selectivity analysis of cod.

Codend	No. of hauls	No. cod in codend	No. cod in cover	Min. length (cm)	Max. Length (cm)
BacomaSS120DD105	8	2520	3139	33	84
T90 SD120	8	1451	5072	33	79
BacomaSS120SD130	8	2918	5236	33	67
BacomaSS140DD105	9	1318	5502	33	92
SS120	10	1185	4859	33	71

TABLE 3: AIC values for the fitting of the different size selection models to the data for cod for the different codends. The lowest AIC values, and hence the selected models, for the different codends are shown in bold.

Codend	Logit	Probit	Gompertz	Richard
BacomaSS120DD105	6425.41	6427.35	**6409.91**	6412.18
T90 SD120	4774.32	**4766.23**	4814.50	4775.97
BacomaSS120SD130	7380.50	**7375.69**	7398.77	7382.35
BacomaSS140DD105	5357.75	5352.82	5353.72	**5349.33**
SS120	5038.38	5048.98	5094.88	**5009.98**

TABLE 4: Size selection results and values for usability indicators for cod for the different codends based on the chosen model (see also Table 3). 95% confidence limits are shown in brackets.

	Bacoma SS120DD105	T90 SD120	Bacoma SS120SD130	Bacoma SS140DD105	SS120
model	Gompertz	Probit	Probit	Richard	Richard
L50 (cm)	38.71 (37.46 – 40.77)	43.36 (41.01 – 44.55)	41.11 (40.06 – 42.02)	45.19 (44.17 – 46.91)	45.59 (43.23 – 47.78)
SR (cm)	7.98 (6.61 – 9.73)	6.66 (5.94 – 7.26)	8.34 (6.91 – 9.57)	10.32 (8.39 – 12.93)	7.16 (6.09 – 9.38)
D	-	-	-	2.71 (0.87 – 100.00)	0.19 (0.10 – 0.86)
nP_{-}	27.7 (19.3 – 35.3)	6.2 (3.6 – 11.5)	18.0 (16.0 – 20.2)	8.15 (6.31 – 10.53)	10.3 (5.6 – 19.5)
nP_{+}	67.6 (55.9 – 75.2)	41.3 (32.3 – 59.2)	56.8 (50.8 – 65.1)	35.15 (30.16 – 39.59)	32.0 (19.8 – 48.5)
nRatio±	0.56 (0.37 – 0.71)	0.18 (0.12 – 0.25)	0.38 (0.32 – 0.44)	0.33 (0.26 – 0.42)	0.43 (0.28 – 0.58)
dnRatio	35.9 (27.1 – 41.6)	15.0 (10.5 – 19.9)	27.3 (24.1 – 30.5)	24.7 (20.7 – 29.8)	30.0 (21.9 – 36.8)
p-value	0.81	0.91	0.95	0.99	1.00
Deviance	30.2	26.9	21.0	24.1	14.6
DOF	38	38	33	42	32

TABLE 5: Summary of hauls used for selectivity analysis of plaice.

Codend	No. of hauls	No. plaice in codend	No. plaice in cover	Min. length (cm)	Max. Length (cm)
BacomaSS120DD105	5	108	8	20	37
T90 SD120	6	488	192	18	43
BacomaSS120SD130	9	1994	1307	17	44
BacomaSS140DD105	8	144	103	20	42
SS120	10	946	73	16	44

TABLE 6: AIC values for the fitting of the different size selection models to the data for plaice for the different codends. The lowest AIC values, and hence the selected models, for the different codends are shown in bold.

Codend	Logit	Probit	Gompertz	Richard
BacomaSS120DD105	43.88	44.02	**43.26**	45.34
T90 SD120	**435.09**	446.60	451.36	436.95
BacomaSS120SD130	3062.77	3061.84	3101.77	**3057.46**
BacomaSS140DD105	276.49	276.73	**274.05**	276.08
SS120	430.36	436.97	**425.35**	427.41

TABLE 7: Size selection results and values for usability indicators for plaice for the different codends based on the chosen model (see also Table 6). 95% confidence limits are shown in brackets.

	Bacoma SS120DD105	T90 SD120	Bacoma SS120SD130	Bacoma SS140DD105	SS120
model	Gompertz	Logit	Richard	Gompertz	Gompertz
L50 (cm)	21.38 (20.23 – 22.27)	24.69 (23.86 – 25.33)	25.16 (24.85 – 25.78)	24.89 (23.93 – 26.44)	20.19 (17.62 – 21.26)
SR (cm)	2.04 (0.10 – 3.82)	2.09 (1.38 – 2.72)	3.94 (3.41 – 5.31)	4.25 (2.64 – 6.27)	2.95 (2.33 – 6.34)
D	-	-	0.45 (0.11 – 0.82)	-	-
nP_{-}	83.7 (67.4 – 95.1)	26.3 (10.0 – 43.5)	30.4 (27.5 – 35.8)	35.6 (19.5 – 49.4)	87.6 (77.0 – 91.6)
nP_{+}	98.6 (92.9 – 100.00)	91.4 (85.9 – 95.7)	76.0 (71.2 – 79.8)	74.0 (61.9 – 84.2)	96.9 (90.4 – 98.3)
nRatio±	0.50 (0.38 – 0.71)	0.12 (0.03 – 0.22)	0.30 (0.22 – 0.38)	0.33 (0.14 – 0.50)	0.69 (0.44 – 0.80)
dnRatio	33.3 (27.5 – 41.4)	11.1 (2.9 – 18.1)	23.1 (17.8 – 27.6)	25.0 (12.1 – 33.1)	40.9 (30.7 – 44.3)
p-value	0.87	0.18	0.67	0.84	0.84
Deviance	9.1	27.9	19.6	12.1	17.0
DOF	15	22	23	18	24

Annex 6:
Understanding the Freswind size selection patterns on Flounder

AN APPLICATION OF COMPUTER-BASED METHODS IN THE DEVELOPMENT OF A FLATFISH ESCAPEMENT DEVICE FOR BALTIC COD TRAWL FISHERY.

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Abstract

In cod directed trawl fishery in the Baltic Sea, considerable amounts of flatfish species are often caught besides the target species and being usually thrown back into the sea owing to its low market value. Because there are low survival expectations for the discarded catch fractions, this practice is seen as an unsustainable waste on natural resources. Fishing technology research in Baltic trawl fisheries has been for long time focused on developing devices for avoidance of cod juveniles, but low effort has been paid in finding ways to jointly reduce unwanted flatfish by-catches, such as flounder. The forthcoming implementation of a discard ban in European fisheries encourages the development of engineering devices to exclude flatfish bycatch from the catch by behavioural stimulation, while maintaining the target species catchability. This study describes the development and test of a flatfish reduction device. The development of the device and the analysis of the collected fishing data to assess its performance are conducted using recent developments in computer-based methods. This includes a combination of bootstrapping techniques and simulation-based methods. Besides analysing the performance of the specific variant of the device actually tested at sea, this combination of computer-based methods enable also to predict the performance of other possible variants of the device and therefore to analyse the potential effect in the fishing environment of different designs.

Keywords

Flatfish, Flounder, species selectivity, trawl, Baltic, *Freswind*, FISHSELECT, behavioral stimulation

1. Introduction

Flounder (*Platichthys flesus*) is the most widely distributed flatfish species in Baltic Sea, mainly caught as bycatch in demersal cod-directed trawl fisheries (ICES 2012). Because the low commercial interest, flounder catches are usually thrown back to the sea with reduced survival expectations after being sorted onboard. Since the approval of a discard ban in EU common fisheries policy for target species, efforts to reduce bycatches and discards in European fisheries have acquired a major dimension in fisheries management in recent times. This new legal scenario enhances fishers and researchers to work together on improving the size and species selection of fishing gears in use.

Cod (*Gadus morhua*) is the main target species in the Baltic trawl fishery making up the catch value in the fishery. The development of selective fishing gears in the Baltic has been primary focused on codend selectivity studies to improve the selectivity of cod. The effort paid in the last decade has given light to multiple factors affecting cod selectivity (Wienbeck *et al.*, 2011; Herrmann *et* *al.*, 2009; Herrmann *et al.*, 2007; Madsen, 2007). In contrast, little research effort has been invested in flatfish selectivity for the time being.

Flatfish species are usually defined as a fish group due to their special physiology, morphology and behavioural features. Such special characteristics are well known by fishing technologist, who in many cases have observed how the burial anti-predatory behaviour and their flat morphology strongly determines i) their herding behaviour in front of the trawl (Ryer, 2008), and ii) the physical process occurring when attempting to escape through the codend meshes (Guijarro and Massutí, 2006; Fonteyne and M'Rabet, 1992; Walsh *et al.*, 1992). It is known that square meshes are more suitable for selectivity properties for roundfish than the standard diamond shape, whereas the opposite is the case for flatfish escapements. These findings illustrate how problematic the traditional management measures, which are based on single species selectivity (i.e. setting T0 codend mesh size), is for multi-specific fisheries having both species groups in their catch profiles.

This paper presents the design, test and analysis of the *Freswind*, a new species selective device developed to reduce the catch of flounders in the Baltic cod directed fishery. The *Freswind* is based on oblique side grids fitted intothe extension section of the gear, in front of the codend. Instead of the usual vertical bars, the grids are made of horizontal bars to match the flatfish body shape in natural swimming orientation. Because it was not primarily designed as a size selection device, the bar spacing was set sufficient wide to allow a wide range of flounder length-classes (hereafter *l*-class) to escape. Results from initial sea trials, carried out in March 2013 on a commercial vessel, demonstrated the potential of this device to reduce flounder bycatch. Interestingly, the descriptive analysis revealed that catch rates have shown an unexpected strong *l*-class dependency when using the *Freswind*-device. The aim of this study is to understand the flounder size selection of this device. The investigation is based on comparing the observed *Freswind* size selection properties to the size selection expected *a priori*. For estimating the observed size selection, we use the experimental data obtained during the trials on the commercial vessel, while the theoretical size selection curves are estimated using the FISHSELECT software. FISHSELECT is a computer-based tool designed to estimate size selection properties of netting meshes and grids for different fish species. Unlike the classical technique based on at sea trials, FISHSELECT theoretically estimates size selection curves by establishing morphological descriptions, lab simulation of selective process (fall-trough experiments) and computer simulations. The method was primary developed and used on roundfish species (Herrmann *et al.*, 2009, 2012; Frandsen *et al.*, 2011; Krag *et al.*, 2011; Sistiaga *et al.*, 2011), Nephrops (Frandsen et al., 2010), and extended to flatfish species in recent times (Herrmann *et al.*, 2013). The latest upgrade of the method was used to understand the sorting grid selectivity of Greenland halibut, including the potential effect of body orientation in relation to the grid bar spacing (Herrmann *et al.*, 2013). This software facility is used herein for investigating if the fish body orientation - when contacting the *Freswind* grid - is a factor which positively interacts with fish length size to condition the escapement likelihood. By using the FISHSELECT, we aim to understand the *Freswind* selectivity on flounder, a necessary step to adapt the original design to future fishing management scenarios.

2. Material and Methods

2.1. Freswind development

The *Freswind* idea was originally proposed by a Swedish fisherman from the Baltic cod trawl fishery. The *Freswind* design is based on inserting an escape windows in front of the codend to specifically improve flatfish escapement rates. The windows are made of 2 steel grids fitted to each lateral side of the gear, at the end of the belly section (Figure 1). The grid bars are horizontally oriented, in a way that the alternate bars represents fissures in the belly matching with the transversal shape of flatfishes. Following the selectivity results obtained for flounder in previous FISHSELECT simulations, the bar spacing was set to 38*mm*, a sufficient bar spacing to allow the escapement for a wide range of flounder sizes, while only smaller cod would have any chance to escape.

Three steering ropes were attached to the front part of the grids and were running to the aft of the extension piece to fix the grids at an angle of 45° in relation to the towing direction. In addition, an inverted V-shaped canvas obstacle was attached in front of the grids area (Figure 1). This obstacle was inserted to alter the flatfish swimming direction sideways to the proximity of the grids. The combination of both - the grid orientation and the guiding obstacle - was expected to improve the contact likelihood of flatfish to the windows, enhancing flatfish escapement probability.

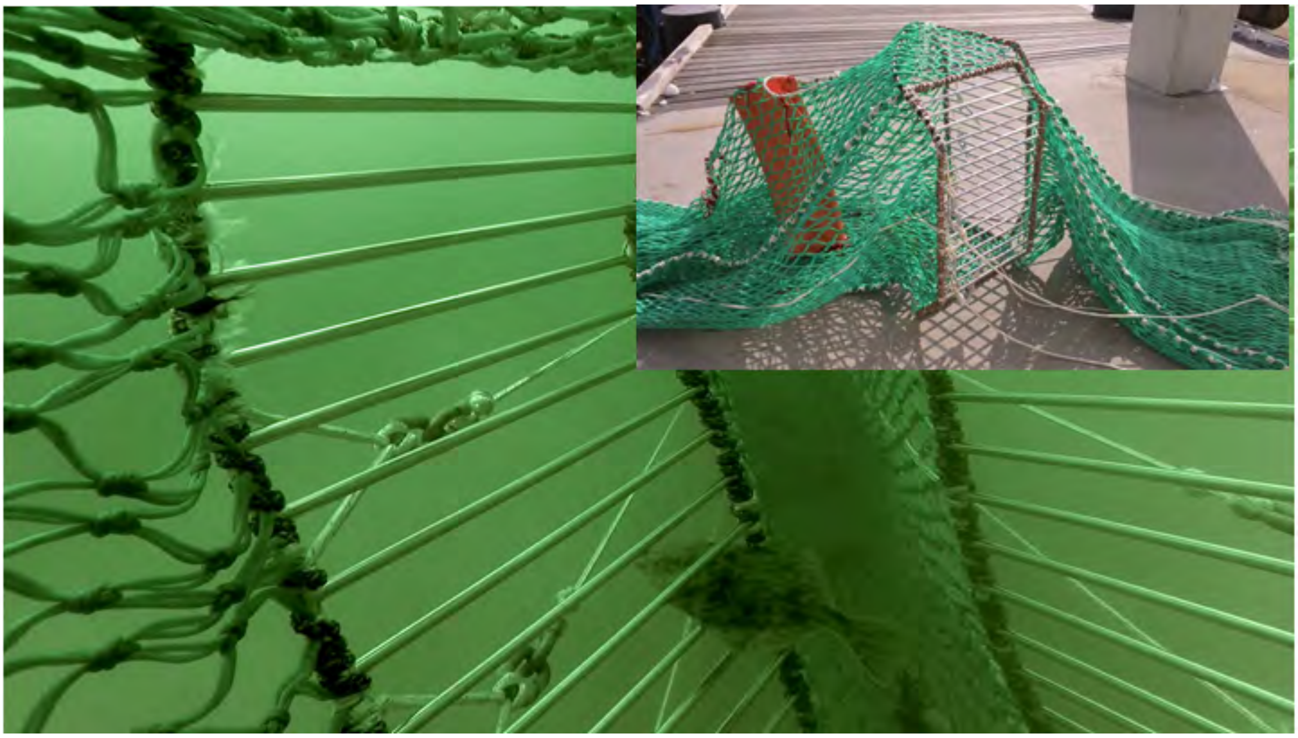

Figure 1 Underwater recording of the *Freswind* during towing and a flounder escaping through the grid (canvas obstacle not shown here). Harbour picture showing the canvas obstacle (top-right).

2.2. Sea trials

The experimental data used for assessing the *Freswind* performance and fish behaviour in relation to the selective device were obtained at sea during a fishing trip performed using a commercial vessel. The first survey was carried out from 15th to 25th March 2013 in the Baltic West of Bornholm area (ICES Subdivision 24) with the aim of estimating the relative difference in catch efficiency between two identical commercial trawl, with the only difference that one of them were mounted with the *Freswind*-device. The gear mounting the *Freswind* is hereafter referred as the *test* gear while the standard one is called the *reference* gear. Both gears mounted the standard BACOMA codends, specially designed to improve cod selectivity. The vessel used was the “Crampas”(SAS 107), a 18 m, 219 kW German twin trawler, which usually participates in the Baltic cod mixed fishery . The twin trawl rigging allows a direct comparison between both gears. We use the data obtained in this cruise to estimate the selectivity properties of the *Freswind*-device for flounder.

2.3. Freswind experimental selectivity analysis

The data obtained during the fishing trip was used to estimate the selective properties of the *Freswind*. The methodology basically follows the standard statistical method for paired gear method (Millar, 1992), but since the *reference* codend was as selective as the codend used in the *test* gear, some adaptations to the Millar (1992) approach have been applied in order to obtain the *Freswind* selection curve. Three prior assumptions are set to develop such methodology:

1. Any flounder caught during the commercial trip had the same probability of entering in both gears, the *test* and the *reference*. This fixed parameter is denoted as split parameter sp=0.5.
2. Except for the gear section where the *Freswind* is located, both gears have the same design; therefore the same selective properties are assumed over the gear sections, except for the *Freswind* section.
3. No fishes used in the analysis can escape through the netting of the extension piece where the *Freswind* is fitted. Therefore, small individuals below 20cm were excluded from the analysis in order to ensure the previous assumption.

Lets n_t^l be the number of flounder of l -class (≥20cm) caught in the test gear, n_+^l be the total number of the same l-class caught in both gears. Under the prior assumptions, the probability of retaining a given fish in each of the gears is:

$$P_{test}(l) = sp * \prod_{i=1}^{q} r_{test,i}\,(l) \qquad (1)$$

$$P_{reference}(l) = (1 - sp) * \prod_{i=1}^{q} r_{ref,i}\,(l) \qquad (2)$$

Where $r(l)$ is a non-decreasing function which describes the retention likelihood in the i-selective section of the gear ($i = \{Freswind, BACOMA\}$). Following the assumption 2,

$$r_{ref,i}(l) = r_{test,i}(l);\ \forall\, i \neq Freswind \qquad (3)$$

Denoting that all i-sections of the gear have the same selectivity except for the section where the *Freswind* is located (hereafter j-section). The probability of finding an individual of a given l-class (≥ 20cm) in the test codend, once it was caught, is:

$$p_{(test|caught)}(l) = \emptyset(l) = \frac{sp * r^{a}_{test,j}(l)}{sp * r^{a}_{test,j}(l) + (1 - sp) \times r^{a}_{ref,j}(l)} \qquad (4)$$

As we only applied length classes above 20cm in the analysis, there are not expectations of escapements through the netting material in the j-section of the reference gear, therefore, we assume $r^{a}_{ref,j} = 1$ for all *l*-classes analysed. In contrast, the *test* gear j-section where the *Freswind* presents selective properties defined by $r^{a}_{test,j}(l)$. We denote $r^{a}_{test,j}(l)$ as r_a (l) to ease the math notations. Based on theory statistics, we assume that the number of flounders in the *test* codend follow a binomial distribution,

$$n^{l}_{t} \sim Binom\left(n_{+}, \emptyset(l)\right) \qquad (5)$$

The log of the binomial mass function is used for a maximum likelihood estimation of $\emptyset(l)$):

$$-\sum_{l} (n^{l}_{t} * log\,\emptyset(l) + \left(n^{l}_{+} - n^{l}_{t}\right) * log(1 - \emptyset(l))) \qquad (6)$$

The function $r_a(l)$ wrapped in $\emptyset(l)$ is denoted as available retention likelihood (Millar and Fryer, 1999), and its functional form is defined by the selective parameters to be used in the comparison with those theoretically estimated by FISHSELECT. Because all fishes might not be affected by the *Freswind* selectivity (as it is not expected that all individuals contact the grids), $r_a(l)$ must be estimated accounting for the contact likelihood (C) of flounder, in order to sufficiently describe the probability of a given *l*-class to be retained by the *Freswind*:

$$r^{a}(l) = 1 - C * \left(1 - r(l)\right) \qquad (7)$$

Where $r(l)$ is a non-decreasing function which describes the dependency of fish retention likelihood on body length. The function *r(l)* is defined as the contact retention likelihood (Millar and Fryer, 1999), and it is specified herein by using the *logit* function:

$$r(l) = \frac{\exp\,(\log(9) \times \frac{(l - L50)}{SR})}{1 + \exp\,(\log(9) \times \frac{(l - L50)}{SR})} \qquad (8)$$

Where L50 is the *l*-class with 50% contact retention likelihood, and SR is the *l*-class range between contact L75 and contact L25. Following the formulations used in Herrmann et al. (2013), the available selective parameters ($L50_a$ and SR_a) are expressed as:

$$L50_a = \frac{SR * \ln(2 * C - 1)}{\ln(9)} + L50 \qquad (9)$$

$$SR_a = \frac{SR * \ln\left(\frac{3 * (C - 0.25)}{C - 0.75}\right)}{\ln(9)} \qquad (10)$$

Using this model, It is possible to estimate the *Freswind* experimental contact retention likelihood ($\widehat{\mathrm{r(l)}}$), defined by $\widehat{L50}$ and $\widehat{SR}$, and the available retention likelihood ($\widehat{\mathrm{r}_a(\mathrm{l})}$), defined by $\widehat{L50a}$, $\widehat{SRa}$, together with the contact likelihood of flounder to the *Freswind* grids ($\hat{\mathrm{C}}$).

Estimation of the 95% confidence limits for the expected *Freswind* retention likelihood was done following the procedure described in Herrmann *et al.* (2012) and Eigaard *et al.* (2012), based on a double bootstrapping technique, which account for within- and between-haul variation in the selection process. A total of 2000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Chernick, 2007; Efron, 1982). The technique is similar to the one applied by Eigaard *et al.* (2011), Herrmann *et al.* (2012), Madsen *et al.* (2012) and Sistiaga *et al.* (2010).
The size selectivity analyses, conducted for the experimental data, were performed using the software tool SELNET. This tool has been widely used in recent years and further information can be obtained from Herrmann *et al.* (2012), Madsen *et al.* (2012), Eigaard *et al.* (2011), Frandsen *et al.* (2011), Wienbeck *et al.* (2011), Sistiaga *et al.*(2010).

2.4 Theoretical Freswind selectivity: the FISHSELECT methodology
We use the FISHSELECT method to theoretically assess the selective properties of the *Freswind* on flounder. A brief description of the different steps is given below. Detailed information about FISHSELECT methodology is available in Herrmann *et al.* (2009), while the description of the software updating to deal with flatfish shape and the effect on body orientation can be found in Herrmann *et al.* (2013).

Step 1 flounder morphological data collection:
This first step involves the collection of selected morphological measurements, length and weight of each individual used in the experiment.

Step 2 Fall-through experiments

Each fish is presented to a series of stiff mesh templates using gravity with the aim of adjusting the measured morphological descriptions with the species potential compression during as mesh penetration. In this study, flounder escapement attempts were simulated on rectangular shapes differing in the width of the rectangle, emulating different bar-spacings of the *Freswind.*

Step 3 Cross-section modelling
The geometric morphometric data obtained in step 1 are used to model the most likely shape of the investigated species on the different cross-section assessed.

Step 4 Penetration modelling
Using a modelling and optimization process, the most realistic compression (changes of geometry) of the modelled cross-section (step 3) were identified to obtain theoretical fall-through results, which have a high Degree of Agreement (DA) with those from step 2.

Step 5 Predictions on the size selection for different grid bar-spacings
Using the previous steps, we theoretically estimate grid size selection for different bar-spacings using the FISHSELECT facilities. The bar-spacing range was M=(20-50 mm), which included the opening used in the *Freswind* experimental cruises (38mm). In these steps, we assume that all fish contacting the grid do it with perfect angle of attack, where fish and bar spacing orientation is equal (we assume this angle to be $\theta=0°$).

Step 6 Size selectivity predictions conditioned to θ
The simulation exercise from the previous step is extended by adding a new simulation dimension, which is the fish body orientation in relation to the horizontal grid bars (θ). We use a range of θ=(5°-45°) in steps of 5° to estimate i=9 different curves, each accounting for a specific θ_i-value. This simulation exercise can be seen as the assessment of the interaction effect of fish orientation on the predicted size selection per grid bar-spacing. This result is presented as a contour plot, where L50 is plotted in relation to grid bar-spacing and the angle of attack to facilitate the global understanding of such interaction.

Step 7 Experimental vs. FISHSELECT curve
We evaluated the degree of similarity between the selectivity curve from the experimental data and the simulated curves, obtained in steps *5* and *6* for 38mm bar-spacing. The resulting curves are denoted as $r(l)_{\theta_i}^{m=38}$. The hypothesis that fish body orientation is a factor which positively interacts with fish length size to conditioning escapement likelihood can be refuted if the assessment shows any of the simulated curves to be close to the experimental curve, both in its intercept and slope. Otherwise, two ultimate steps would be necessary to assess the effect of θ on *Freswind* size selection:

Step 8 Prediction frequencies of θ grid size selection and comparison to sea trial results

In case of misfit between the experimental curve and any single $r(l)_{\theta_i}^{m=38}$, we use the selectivity properties obtained in previous steps to investigate at what extent the shape of the experimental selection curve can be explained assuming different fish orientations when contacting the grid (θ_i) or even more, assuming that not all fishes come into contact with the grids. This exercise is carried out using the FISHSELECT simulation facilities described in Herrmann *et al.* (2013) and is based on simulating virtual flounder populations to evaluate the grid selectivity, assuming that fishes come into contact with the grid might do it at different θ. FISHSELECT enables the estimation of the relative contribution of each of θ_i that would best be able to reproduce the experimental selective curve. The resulting simulated curve is denoted as $\widehat{r(l)_{\theta_{comb}}^{m=38}}$

Step 9 Theoretical estimation of different bar-spacing selectivity

Finally, we re-estimated grid size selection at different bar-spacings using the FISHSELECT facilities as described in step 5, but using the combined orientation modes (θ_{comb}) estimated in step 8. The resulting curves are denoted as $r(l)_{\theta_{comb}}^{m}$.

3. Results

3.1. Freswind experimental selectivity analysis

A total of 13 valid hauls were carried out during the commercial cruise. The total flounder catch was ~890kg, of which 270kg were observed in the *test* codend (~30%). Consequently, the flounder catch using *Freswind* was reduced by ~56% in weight compared to the *reference* trawl. The total catch in numbers was 4770 individuals, of which 1333 individuals were found in the *test* (~28%, equivalent to a reduction of ~61%). This percentage differs between *l*-class groups (considering the Minimum Landing Size [MLS]=23cm as grouping factor), showing that the relative catch decreases to ~41% for the group of sizes above MLS, while the reduction was even stronger for undersized individuals (31.2%). Table 1 show the resulting size selection parameters obtained from the experimental data analysis. The used model estimated a high contact likelihood ($\hat{C} = 0.81$), which means that 81% of flounders entering the test gear are expected to contact the *Freswind* grid. The upper confidence interval for this parameter was 1.0, therefore there is no significant evidence that the contact likelihood is different to 100% of all individuals entering the test gear. *Freswind* selective parameters and the available selective parameters did not differ substantially, due to the high contact likelihood estimated. The available 50% retention *l*-class parameter ($L50_a$) was ~33cm (28.1-46.2) while the SR_a was

15.7cm (0.3-54.5), indicating a wide l-class range between the available 75% and 25% retention l-class. The predicted selective parameters describe the experimental catch rate curve ($\widehat{\emptyset(l)}$) and the experimental contact $\left(\widehat{r\ \ (l)}\right)$ and available $\left(\widehat{r_a(l)}\right)$ retention curves showed in Figure 3.

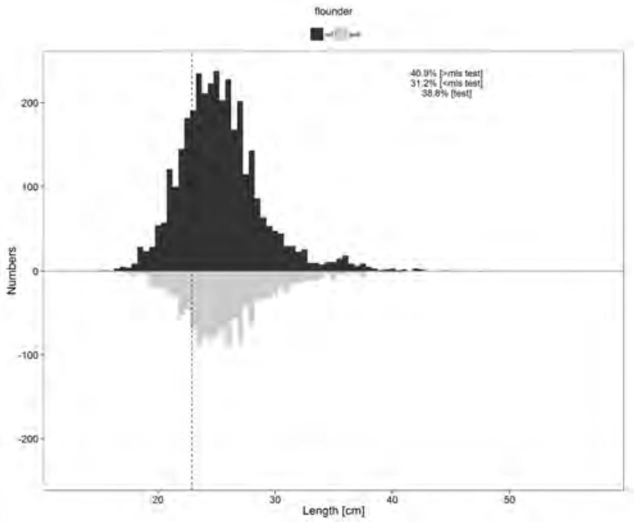

Figure 2. Length distribution of flounder per trawl (reference trawl (ref) and test trawl (test)). Percentages show the catch (in numbers) obtained in the test gear in relation to the reference one (100% value means equal catch) by length group categories (above MLS, below MLS and full length range). Sign of test counts were changed to negative values to facilitate the comparison.

Table 1. Estimated size selection parameters and bootstrap confidence intervals (in brackets) using the experimental flounder data. The model used assumes an equal split of catches (fixed split value sp=0.5), which is reflected using the * symbol.

Parameter	Estimation
$\widehat{L50}$,	31.07 (27.36-40.88)
$\widehat{SR}$	15.49 (--58.93)
$\hat{C}$	0.81 (0.61-1)
$\widehat{L50}_a$	32.97 (28.16-46.28)
$\widehat{SR}_a$	15.74 (0.31,54.57)
*sp**	0.50
AIC	5473.63

P-Value 0.0796

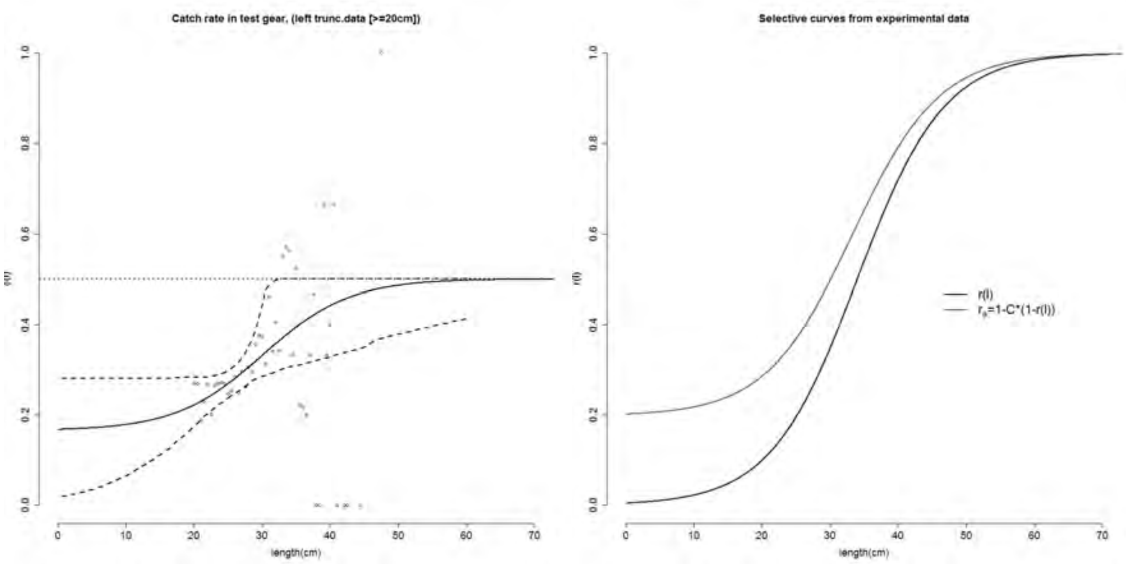

Figure 4. Left: Catch rate curve ($\widehat{\emptyset(l)}$) and the associated bootstrap confidence intervals estimated for Flounder in the test codend (*Freswind*). Values around Ø(l)=0.5 indicates no size selection added by the use of the *Freswind*. Right: full ($\widehat{r(l)}$) and available ($\widehat{r_a(l)}$) retention likelihood estimated for the *Freswind*. The intersect of ($\widehat{r_a(l)}$) is raised to ~0.2, matching with the fish proportion not contacting with the selective device (~20%).

3.2. Theoretical Freswind selectivity and the effect of fish orientation θ

For a bar-spacing of $38mm$, the simulation estimated a $\widehat{L50_{\theta=0}^{m=38}}$ of more than 50cm (Figure 5 left), far above the experimental $\widehat{L50}$ ($\sim 31.1cm$), indicating a clear mismatch of both estimations, when assuming that all fishes contacting the grid do it at perfect angle (θ=0°). It was found, that the experimental curve $\left(\widehat{r\ \ (l)}\right)$ does not match any of the theoretical curves with fixed θ ($\widehat{r(l)_{\theta_l}^{m=38}}$) (Figure 5 right). This indicates that flounder hit the grid at different angles and therefore, the experimental curve might be a result of a combination of curves with different θ. The combined simulated retention curve ($\widehat{r(l)_{\theta_{comb}}^{m=38}}$), obtained from FISHSELECT step 8, showing the largest degree of similarity with the experimental curve $\left(\widehat{r\ \ (l)}\right)$ was obtained from a mixture of $\widehat{r(l)_{\theta_l}^{m=38}}$ which contributed with different weights (Table 2, Figure 6). The simulation estimated that $\sim 87\%$ of individuals contact the grid at an angle of attack θ≤20°, and the most frequent contact angle was 10°. The simulation estimates that the contribution of wider angles of attack 20°<θ≤45° only contributed with ~13 to the $\widehat{r(l)}_{\theta_{comb}}^{m=38}$ definition.

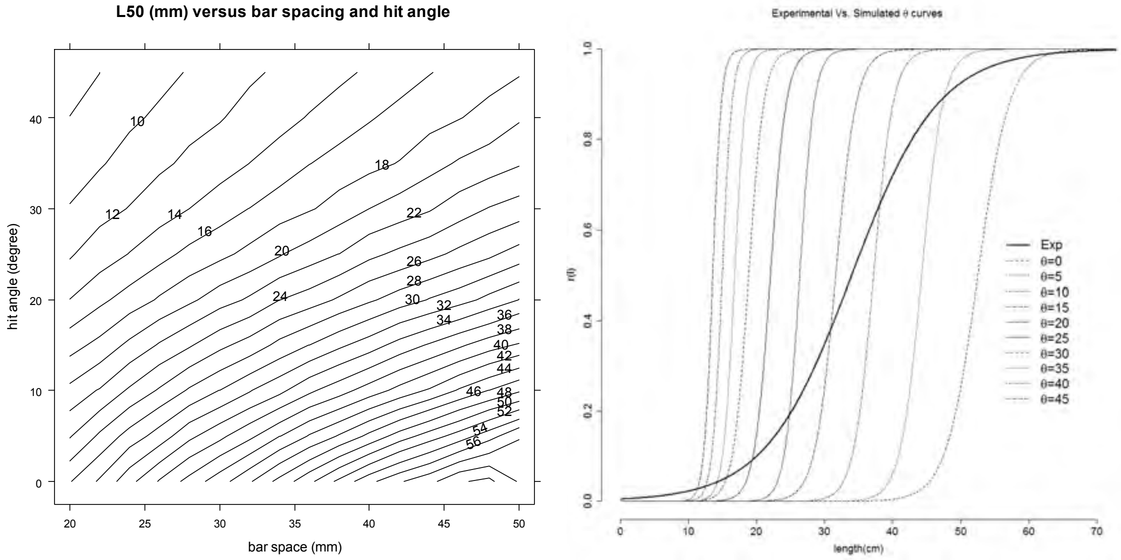

Figure 5. Left: Countour plot showing the effect of bar-spacing and the hit angle of the fish to grid on L50 Right: comparison between the experimental retention curve (solid thick line) and the different simulated curves (dotted thin lines). Each of the simulated curves assume a fixed fix contact mode (θ=0°-45°).

Table 2 Predicted contribution of each $\widehat{\mathrm{r(l)}}_{\theta_1}^{m=38}$ to produce the combined simulated retention curve ($\widehat{\mathrm{r(l)}}_{\theta_{comb}}^{m=38}$) which is optimized to match to the experimental retention curve.

Theta (θ)	Contribution (%)
0	10.3
5	15.86
10	22.13
15	17.69
20	21.03
25	3.09
30	0.01
35	3.72
40	2.24
45	3.92

Figure 6 shows the high similarity achieved between $\widehat{r(l)_{\theta_{comb}}^{m=38}}$ and the experimental curve $(\widehat{r(l)})$, while the Figure 7 shows the result of estimating grid size selection at different bar-spacing using the FISHSELECT, using the combined orientation modes (θ_{comb}) which better explain the experimental curve. The resulting curves are denoted as $\widehat{r(l)_{\theta_{comb}}^{m}}$ for the contact retention curves (Left) and $\widehat{r_a(l)_{\theta_{comb}}^{m}}$ for the available retention curves.

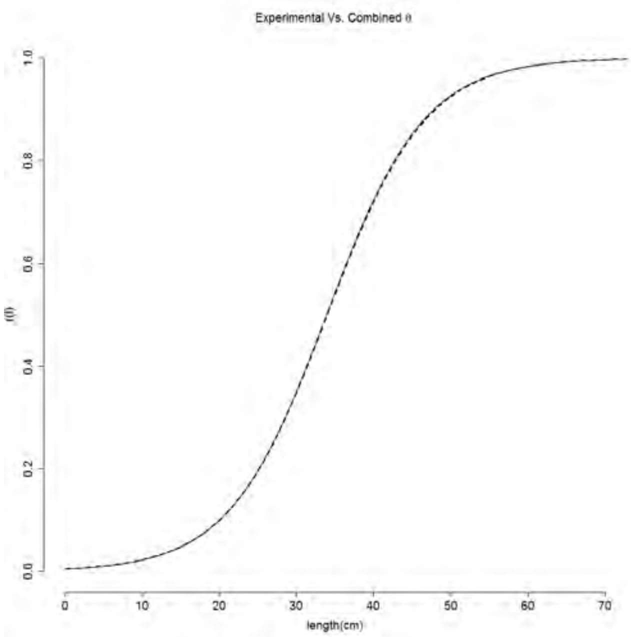

Figure 6. Comparison between the experimental retention curve ($\widehat{r(l)}$, solid line) and the FISHSELECT simulated curve based on the optimal combination of θ which reproduces the experimental curve ($\widehat{r(l)_{\theta_{comb}}^{m=38}}$, dotted line).

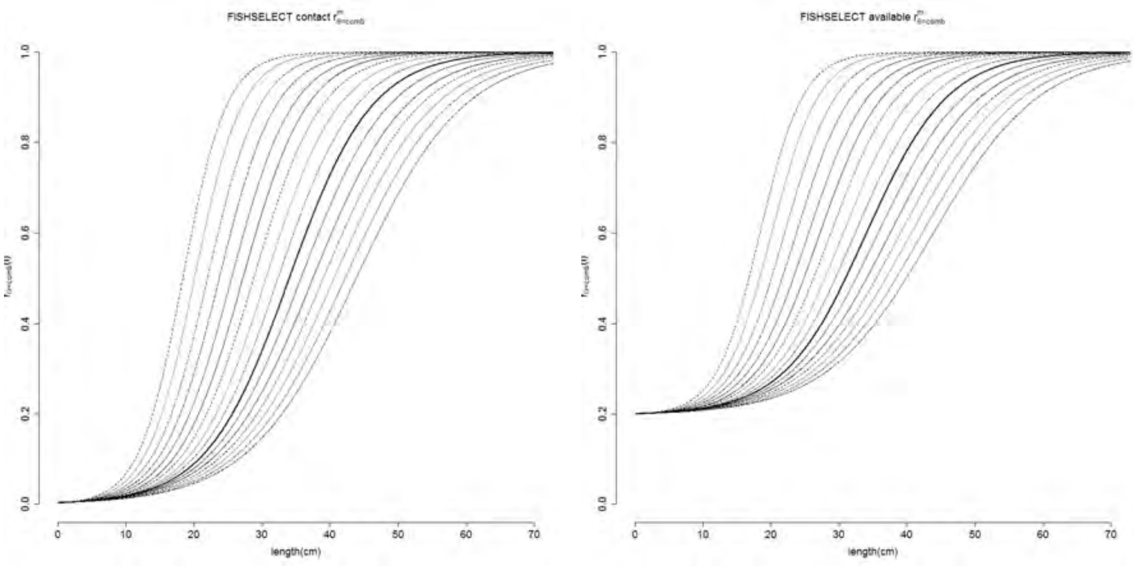

Figure 7. Left: Estimated $r(l)^{m}_{\theta_{comb}}$ curves with m representing different bar-spacing, from $20mm$ to $50mm$ in steps of $2mm$. Right: Estimation of available retention likelihood for the same bar-spacing set and considering the contact likelihood estimated for the experimental data $r_a(l)^{m}_{\theta_{comb}}$.

Discussion

The analysis of the sea trial data has shown that the use of the *Freswind* reduced ~56% of flounder catches in weight (61% in numbers) while no significant reduction of the primary target species cod was found (information not presented here). These results confirms that this device can substantially reduce the unwanted bycatch of flounders in the Baltic cod fishery and could be a promising species selection device to reduce flatfish catches in other mixed fisheries, where roundfish species are the target.

The bar spacing used during experimental fishing was chosen as compromise between largest possible grid spacing to increase the possibility of flatfish escapement, and simultaneously to avoid loss of cod above minimum landing size. Whereas the selective properties of the grid with 38mm bar spacing – under the assumption of optimal hit angle - would result in a L50 of around 50cm for flounder, the experimental selectivity was much poorer. Consequently, other factors influence the retention likelihood of flounder in relation to *Freswind*.

Herrmann *et al.* (2013) concluded that flatfish body orientation plays a major role in the definition of the sorting grids selection curves. They investigated the contribution of different hit angles on the selectivity of Greenland halibut in relation to a grid with vertical bars, where most fish seem to escape at an angle of $\theta > 50°$ (θ=0 refers to vertical orientation of fish). The results for the *Freswind* have also indicated the possibility of relatively large hit angles, whereas the majority of flounder is estimated to hit the grid at a relatively small angle ($\theta \leq 20°$), compared to the optimal orientation in relation to the grid. This is consistent with the different bar orientations in both studies. For a given flatfish escaping through the vertical bars it is required a dramatic body turn from their natural position to fit to the vertical bar-space. Since the *Freswind* grid is based on horizontal bar spacing, most of the flatfish escaping will do it at low θ values, meaning that they don´t need to change their natural body orientation as in case of vertical grids for Greenland halibut.

The *Freswind* was designed in a way that the grids do not block the cross section of the extension completely. Such design implies that not all individuals may contact the grids on their way to the codend, as observed during the experimental study ($\hat{C}$~0.81). Under this situation, it could be argued that the mismatch between the simulated and experimental retention curves might be explained by length dependent fish avoidance behaviour. Under this additional hypothesis, larger individuals might perform stronger swimming to avoid the contact with the escapement window, reorienting its swimming direction to the free flow net tunnel into the codend. This alternative hypothesis was rejected after inspecting the UW video footages showing flounder behaviour in relation to the *Freswind* grids.

Using the simulation tools available in FISHSELECT and the experimental testing under real fishing conditions, it has been given light to the underlying factors explaining the mismatch between the expected and the actual selective properties of the *Freswind*. This information is relevant for fishermen, gear technologists and fishing managers to allow a better decision-making towards the best selective device specification to be used in a given fishery. The *Freswind* will also provide fishermen with a selective device by which they can avoid unwanted bycatch of flounders which is expected to be highly relevant with the coming discard ban in the Baltic and bordering waters.

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Annex 7:
Using penalized regression splines for estimating catch comparison curves in pair trawl experiments

Using penalized regression splines for estimating catch comparison curves in pair trawl experiments

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1 Introduction

Catch comparison experiments aim to produce statistically sound estimations of the relative difference in catch efficiency between (at least) two gears under study. Although catch comparison is the general methodology used in Bottom Trawl Surveys calibrations, It also has emerged as an alternative tool in selectivity studies in recent times for several reasons:

- It does not require extra-rigging (cover codends), or non-selective codends attached to the gear during the data collection. This is a clear advantage during the practical implementation of the experimental design in commercial vessels.
- The workflow onboard is similar to the commercial fishing activity.
- In contrast to the covered codend methodology The number of compartments to be sampled is reduced to one per gear tested.
- The results from the comparison can be better understood by fishermen than the outputs from the selectivity models (Catch more than/less than).

A common experimental design in this kind of studies implies the use of a *reference* gear (e.g. a commercial specification) and a *test* gear (new specification including one or more selective improvements) for comparison. In order to achieve better results (in terms of precision), it is highly recommended that both gears fish on the same populations, in the same area, same physical conditions and if possible at the same time. The so-called paired gear experiments (Willeman *et al*, 1996), which includes trouser

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trawls, twin trawls, paired hauls, alternate hauls experiments, are considered the best experimental setting to reduce the potential violation of the recommendations mentioned above .

The commercial sea trials of this project has been conducted using twin trawl methodology. The twin trawl rigging allows towing two gears simultaneously during the same haul, which reduces potential source of variation from another alternatives of paired hauls.The vessels were selected in relation with their representativeness of the target fishery (Baltic cod mixed fishery).

Generalized Linear Mixed Modeling (GLMM) is broadly used by fishing technology researches in catch comparison studies. The aim is the estimation of a curve representing the catch ratio of the *test* relative to the *reference* trawl over the fish length classes available. Together with the estimation of length effect on catch rate (fixed effect), the GLMM technique allows the modeling of sources of variation affecting the observed catch rate. Such sources of variations (random effects) are usually defined as the different sampling units nested in the multistage sampling protocols commonly used in fishing studies. By modeling the random effects, it is possible to obtain different components of variance, which added to the variance of the fixed effect produce reliable Confidence Intervals (CI) for the predicted curve. One disadvantage of this methodology is that the length effect is estimated as a linear coefficient. To overcome this restriction Holst and Reville (2009) proposed the use of polynomials to smooth the length size effect in cases where such effect is not linear. The authors controlled the degree of smoothness under the Wald test criteria. The degree of smoothing is therefore defined by the first significant polynomial order (backward stepwise model selection). GLMM framework is a very complicated regression technique which in many cases can produce unexpected results difficult to understand by non-experts in mixed modeling. For the Lot-1 catch comparison studies we use an alternative methodology based on using penalized regression splines (Wood, 2006). Curves variation was simulated by resampling methods, and the Confidence Intervals were estimated using the percentile-bootstrap method (Efron, 1993). Herein it is presented the basis of the curve estimation using the p-spline methodology.

2 Experimental design and model definition

Let n_t be the number of fish caught in the *test* gear, n_r the number of individuals caught in the *reference* gear, n_+ the global catch, and

$$p = \frac{n_t}{n_+} \tag{1}$$

Be the catch ratio in *test* . The catch ratio (p) only can take values between 0 and 1. If $p \sim 0.5$, then it is assumed equal fishing efficiency for *test* and *reference* gear, $p < 0.5$ means lower efficiency in test and the opposite when $p > 0.5$. Based on theory statistics, we assume that the number of fishes in the *test* codend follow a binomial distribution,

$$n_t \ Binom(n_+, p) \tag{2}$$

Because we are interested on the effect of length size in the catch ratio, the earlier can be derived to

$$n_t(l) \ Binom(n_+(l), p(l)) \tag{3}$$

Being l the fish length size. The fact that the response only can take values between 0 and 1 violates the basic assumptions of standard regression tools, therefore, to estimate the p(l) curve we use regression tools specially developed to deal with binary data. The underlying approach is to transform the response into a linear form $[-\infty, \infty]$. In this case, we use the logit link function:

$$logit(l) = lnOdds(l) = ln(\frac{p(l)}{1-p(l)}) \tag{4}$$

The classic logistic models perform a linear approximation of the effect of l on the *test* catch rate:

$$p(l) = \frac{\exp(\beta_0 + \beta_1 \times l)}{1 + \exp(\beta_0 + \beta_1 \times l)} \tag{5}$$

To allow certain degree of smoothness of the effect of l on the catch rate, we use penalized regression splines (Wood, 2006) instead of a full parametric estimation:

$$p(l) = \frac{\exp(\beta_0 + f_1 \times l)}{1 + \exp(\beta_0 + f_1 \times l)} \tag{6}$$

The resulting p(l) is therefore the relative catchability curve of fish in test codend.

3 Curve estimation using Penalized Regression Splines

To estimate the unknown function f_1 (see eq. 6) , firstly it is defined as a spline basis:

$$f_i(l) = \sum_{k=1}^{K} b_k(l)\beta_{1k} \tag{7}$$

Where $b_{1k}(.), k = 1, \cdots, K_1$ are known functions, K_1 is the the number of nodes and β_{1k} is an unknown parameter.

Under this formulation, the functión f_1 becomes a parametric form depending exclusively on the estimation of the parameter $\beta_{1k}(.), k = 1, \cdots, K_1$. The method is also available in the GLM framework:

$$\eta_i = \sum_{k=1}^{K_1} b_{1k}(x_{1i})\beta_{1k} + \ldots + \sum_{k=1}^{K_p} b_{pk}(x_{pi})\beta_{pk} = \mathbf{X}_i\beta \tag{8}$$

where η_i is in our specific case the link function showed in eq. 4. At this stage, it could be considered to use the estimation technique from the GLM framework, nevertheless the number and the positions of the smoothing nodes must be predefined. A way to overcome such problem is to set a large number of nodes as default, and to control the degree of smoothness by including a penalty in the estimation process

$$\sum_{i=1}^{n} W_i \left(Z_i - \mathbf{X}_i\beta\right)^2 + \lambda_1 \int \left(f_1''(X_1)\right)^2 dx_1 + \cdots + \lambda_p \int \left(f_p''(X_p)\right)^2 dx_p \tag{9}$$

Where the integral of the squared second derivative (9) estimates the degree of curvature of each of the smoothing functions, being penalized by λ_j (the smoothing parameters). In such penalized residual sum of squares estimation:

- $\lambda_j \to \infty$ leads to estimate f_j as a linear function.
- λ_j=0 leads to the interpolation of data.

The estimation of λ_j values is therefore one of the most important steps in regression using penalized splines. Different criteria can be used to the optimal λ_j selection. Among other, Cross Validation (CV), Generalized Cross Validation (GCV), or Akaike Information Criteria (AIC), or specifically for binary data the Un-Biased Risk Estimator (UBRE).

To estimate the catch comparison curves with p-spline smoothing we used the package `mgcv` (Wood, 2006), available in `R` (R Development Core Team 2012) repository.

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