Avoiding the by-catch of boarfish in pelagic trawling

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Summary

The Dutch pelagic freezer trawler group (Redersvereniging voor de Zeevisserij, RVZ) wishes to avoid the by-catch of non-target species such as boarfish (*Capros aper* L.) as much as possible. This species is unsuitable for human consumption, and when present in the fishing gear with other species they will reduce product quality. A project was set-up in the VIP-programme. The goal of this project was to reduce the by-catch of boarfish as much as possible by early recognition of this species in echograms and technical trawl adaptions. This report focuses on the results of the acoustic work.

Acoustic boarfish data recorded at multiple frequencies (38, 70, 120, and 200 kHz) were collected opportunistically by a freezer-trawler during a fishing trip targeting mackerel and horse mackerel. These acoustic boarfish data were then compared to data of mackerel and horse mackerel in an attempt to distinguish these species based on the acoustic signatures. In order to get more insight into the acoustic properties of boarfish in general, the reflection of sound by boarfish was also modelled based on MRI scans of fish and swimbladders.

The measurements and modelling results concluded that the boarfish echo gets relatively weaker at the higher frequencies used. In terms of practical fish classification, however, boarfish reflects sound at the analysed frequencies in a similar way as horse mackerel. While these two species may be distinguishable from mackerel, overall multifrequency distinction of all three species together (using frequencies of 38, 70, 120, and 200 kHz) still remains impracticable: distinction between either ‘horse mackerel & mackerel’ OR ‘boarfish & mackerel’ using the said four4 frequencies has a high potential for success. However, if all three species are taken together, the identification of horse mackerel and boarfish is “blurred” due to their similarities. Bad classification results are also expected if just boarfish and horse mackerel are compared with each other, due to their acoustic similarities.

1. Introduction

The Dutch pelagic freezer trawler group (Redersvereniging voor de Zeevisserij, RVZ) wishes to avoid the by-catch of non-target species such as boarfish (*Capros aper* L.) as much as possible. This species is unsuitable for human consumption, and when present in the fishing gear with other species they will reduce product quality.

A project was set-up in the VIP-programme. The goal of this project was to reduce the by-catch of boarfish as much as possible by early recognition of this species in echograms and technical trawl adaptions.

In the development phase of this project the detailed work plan was produced and the potential for using acoustic software adaptations to distinguish boarfish from other pelagic species was explored. The idea was to use multi-frequency echo-sounders for species identification to distinguish boarfish from other fish species before capture, based on their acoustic signatures.

In addition to the acoustic approach, selective net devices were designed by the company Maritiem Ltd. of Katwijk, the Netherlands and tested. However, this report focuses on the results of the acoustic work. The net innovation part is dealt with in a separate report (Pastoors et al., 2014).

2. Materials and Methods

Literature review

A review was made of relevant investigations in to the behaviour of pelagic species, and technical solutions such as net innovations used to improve species selectivity (See Appendix A).

Acoustic data of boarfish collected on SCH6 ”Alida”

As part of another dedicated project aimed at acoustic distinction between mackerel and horse mackerel (project: "Towards improved selectivity of Atlantic mackerel and horse mackerel using scientific acoustic species identification methods", involving IMARES and RVZ company ‘W. van der Zwan & Zn’), acoustic data were collected at multiple frequencies (38, 70, 120, 200 kHz) on the SCH6 (F/V ‘Alida’).
During fishing trips targeting mackerel and horse mackerel in the western English Channel, acoustic data containing schools of boarfish were also recorded, as the vessel encountered and caught that species there (see Figure 1). However, there was no dedicated fishery on boarfish, therefore the data contained much more examples of horse mackerel and mackerel and any boarfish detections were purely opportunistic. A total of 16 identified boarfish schools could eventually be extracted from the data for further classification analysis.

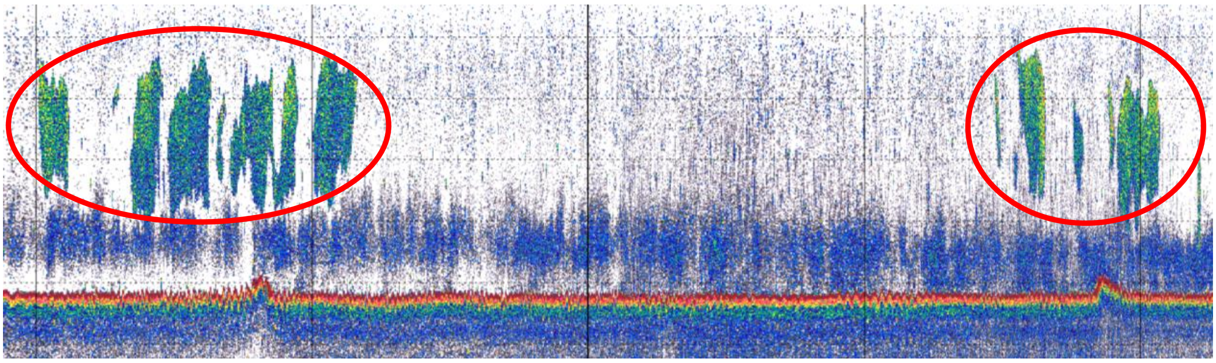


Figure 1. Boarfish schools (shown inside the red circles) recorded opportunistically on SCH6 "Alida" during a horse mackerel & mackerel fishing trip. This example shows an echogram recorded at 38 kHz.

Boarfish samples used for acoustic scatter modelling

In order to model the a acoustic backscatter of the baorfish, biological samples had to be collected for further MRI scanning to derive the 3D shape of the main scatter organ, the swimbladder. Some boarfish samples were collected onboard the Irish commercial vessel FV "*Felucca*" during the dedicated boarfish acoustic survey. Time between shooting and recovering the net ranged from 31 - 69 minutes and individual samples used in this study were only collected from schools at the upper depth distribution limits observed (<40 m). This was to ensure that the depth-adapted boarfish swimbladders were minimally affected by the catching process. For the backscatter model to derive reliable estimates from the boarfish swimbladders, they should ideally be intact, non-collapsed, and inflated to a depth-adapted state, in which the fish are neutrally buoyant. In total, 43 specimens covering the size range 12-17.5 cm were collected from the trawl catches and stored frozen. To confirm that the swimbladders of the boarfish samples remained intact after capture and handling, at least one individual from each 0.5 cm length class was selected for radiography. Each individual was X-rayed in the lateral and dorso-ventral position. Magnetic resonance (MR) images of transverse sections of the fish were subsequently collected. 3-D representations of the swimbladders from the MRI image slices were then reconstructed. The high image contrast between the gas-filled swimbladder and surrounding tissue enabled accurate assessment of the swimbladder boundaries (Figure 2). The swimbladder of each boarfish sample was built up from its individual cross-sections on all individual image slices of the combined scanning sequence.

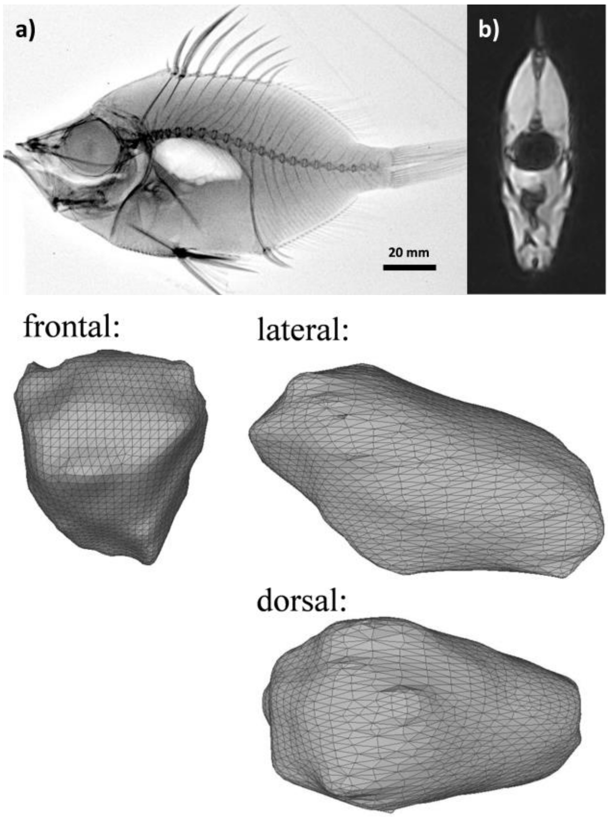


Figure 2. Lateral X-ray (a) and axial MRI section from the central portion (b) of a 175-mm boarfish sample used for TS modelling. Below: three-dimensional reconstruction of the swimbladder, represented as a wire frame composed of triangles shown at different aspects.

Modelling acoustic properties of boarfish

Currently, the knowledge of acoustic scattering properties is available for important commercial species or species groups that have historically been well covered by acoustic surveys. These properties are usually explored based on experimental measurements of immobilised or dead fish, fish in cages, or observed alive in their natural habitat. Recently, with advances in computing power, increased amounts of effort have been going into estimating acoustic reflectivity of fish through the use of sound scattering models based on morphological and physical data of the fish. Such models have the advantage that, given appropriate input data, they can produce reliable estimates of scattering properties in the absence of any other available measurements.

Acoustic backscatter of the collected boarfish samples was modelled at 5 typical frequencies (the 4 frequencies available on the SCH6 (F/V ‘Alida’), and 18 kHz) using the 3-D swimbladder shapes and applying the Kirchhoff ray-mode (KRM) approximation (Fässler *et al*., 2013). The fish body was represented as a set of fluid-filled cylinders surrounding the gas-filled cylinder sections of the swimbladder. Total fish backscatter was calculated as the coherent sum of both swimbladder and fish body cylindrical elements. The swimbladder was assumed to be gas-filled with a density of 2.64 kg m^{-3}, while the fish body component was assumed to be fluid-filled with a slightly higher density (1070 kg m^{-3}) than the surrounding sea water (1027 kg m^{-3}). Speed of sound in sea water, fish body and swimbladder were 1500, 1570, and 340 m s^{-1}, respectively.

Avoiding the by-catch of boarfish by multifrequency acoustic species recognition

Acoustic identification of fish species

The use of more than one frequency in fisheries acoustics may improve the accuracy of allocating detected fish schools to species, especially if the acoustic properties of different fish species encountered vary with the frequency in use. Such techniques have been used previously during scientific acoustic ecosystem monitoring to better discriminate between groups of fish, small krill and zooplankton, and also for discrimination between biological targets and physical phenomena such as air bubbles. However, multifrequency processing techniques have also been commonly used by scientists to distinguish various commercial target fish species such as mackerel, herring or sandeel. Indeed, the difference in the acoustic backscatter intensity between different frequencies has been described as one of the most promising methods for acoustic species identification.

Pre-processing of the multifrequency data by accounting for transducer positions and transmission delays in the receiver improves the spatial comparability between data collected at different frequencies. Acoustic recordings should also be corrected for ambient noise (an important factor reducing the quality of the data on fishing vessels) and smoothed to reduce variation. Multifrequency data provide the relative frequency response r(f), which is then used to distinguish various acoustic categories. **r(f) is defined as the ratio of the backscattered energy at frequency (f) to that at 38 kHz (where 38 kHz is the reference frequency)**. This method has previously been used with success to distinguish scattering groups with a high spatial resolution. A typical example is the grouping of acoustic data into acoustic categories, such as: Atlantic mackerel, which do not have a swimbladder, other fish with swimbladders, resonant scatterers, and zooplankton. However, this approach is limited when trying to distinguish between fish species with similar acoustic properties. Moreover, an echogram may show a single school but it may be the product of a mixed species aggregation.. The uncertainty can be addressed by generating mean acoustic measures from different cells (segments) of the school (Figure 3), thereby classifying different parts of a school rather than averaging it as a whole. Then, observed acoustic properties can be compared with test results from caught and verified fish schools to establish whether they belong to a certain species (cross-validation).

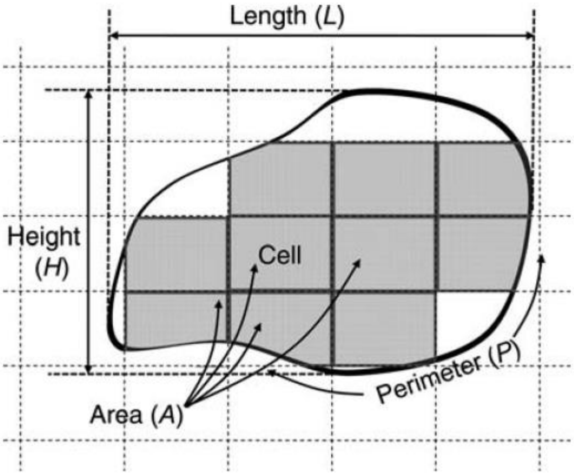


Figure 3. Cells representing fish school sub-sections used in analysis of acoustic school-level data (source: Korneliussen et al., 2009).

In any case, acoustic properties of to-be-identified fish species first need to be characterised at different frequencies, either from field data or by modelling. Such information can then be used to build up training data sets and develop objective classification algorithms. These could then be implemented in software tools for practical real-time classification to assists skippers on the bridge with catch decisions. Existing software tools such as Echoview (Myriax, Hobart, Australia) or LSSS/SEAT (Marec, Norway) could be used to implement such methods (Figure 4). Only acoustic test data verified by finding a single (or very dominant) species in associated trawl catches should be used as a basis for species recognition libraries in order to avoid contamination.

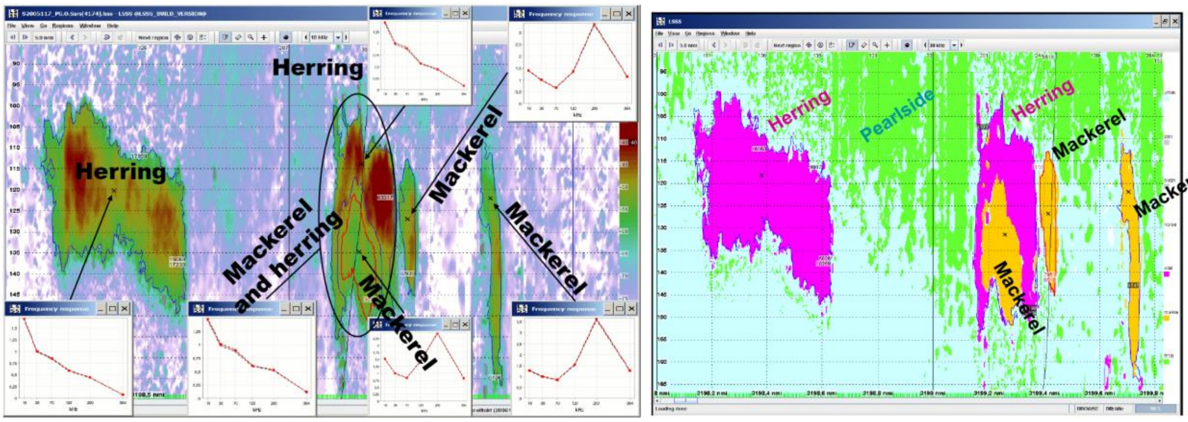


Figure 4. Example of detected fish schools and subsequent classification based on the species' individual typical acoustic backscatter at different frequencies (LSSS software; source: Rolf Korneliussen, IMR, Norway).

3. Results

Modelled acoustic backscatter of boarfish at different frequencies

The backscatter of boarfish modelled at 5 typical frequencies (18, 38, 70, 120, and 200 kHz) showed a decreasing relative frequency response r(f) with increasing frequency (Figure 5). r(f) at 120 and 200 kHz gave similar values of 0.71 and 0.70, respectively (meaning that backscatter at these frequencies was on average 71% and 70% of the backscatter at 38 kHz). In comparison to these, r(f) values at 18 and 70 kHz were slightly higher at 0.90 and 0.85. These attributes could generally be linked to the observed shift in maximum observed backscatter towards 10-15º head-down tilt orientation of the fish with increasing frequency (Fässler *et al.*, 2013). This resulted in lower mean backscatter at progressively higher frequencies relative to 38 kHz. Lower relative frequencies at 18 kHz were due to the lower absolute value of maximum backscatter at that frequency relative to 38 kHz.

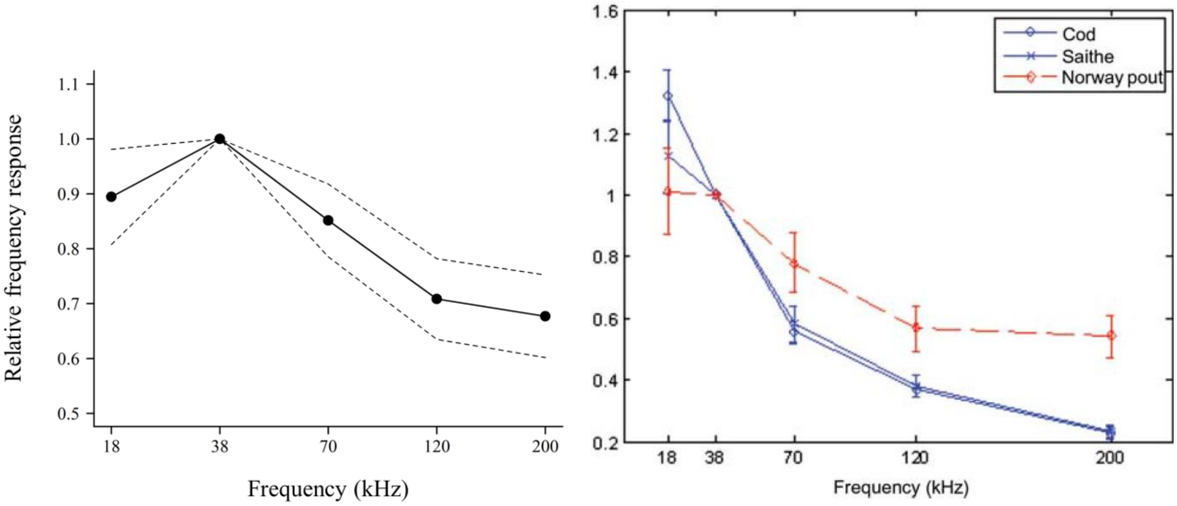


Figure 5. Left panel: Frequency-dependent backscatter of boarfish predicted by the Kirchhoff-ray mode approximation at typical frequencies used in fisheries acoustics (18, 38, 70, 120 and 200 kHz) relative to the backscatter at 38 kHz (i.e. relative frequency response). Filled dots represent mean values with 95% confidence intervals (dashed lines) (source: Fässler et al. 2013). Right panel: Measured relative frequency response of three gadoid species (source: Pedersen and Korneliussen (2009)).

Common with other investigations on multifrequency backscattering properties of fish species with closed swimbladders, the boarfish showed a decrease in r(f) from 38 kHz towards higher frequencies. The rate of this decrease is primarily dependent on the typical average size of the fish species. In that respect, the modelled boarfish r(f) values shown here (Figure 5) were comparable to those reported for Norway pout (*Trisopterus esmarkii*), another small-bodied physoclist species. On the other hand, the fall in r(f) from 38 kHz towards higher frequencies was much more severe for cod and saithe, which both have a larger average size (Figure 5). Given this typical physoclist frequency response exhibited by boarfish, there is a potential to separate them from species that have different backscattering properties with use of multifrequency acoustic methods. Especially in the case of Atlantic mackerel (*Scomber scombrus*), which shows an increasing trend in r(f) from 38 kHz towards 200 kHz and co-occurs with boarfish in space and time.

Acoustic multifrequency data of boarfish collected on SCH6 (F/V ‘Alida’) and classification in software

The acoustic boarfish data collected on SCH6 ‘Alida’ during fishing trips targeting mackerel and horse mackerel are volume backscatter values represented by pixels in the echogram. The boarfish data were attempted to be included as training dataset in the SEAT/LSSS software (Marec, Norway) in a similar way as for mackerel and horse mackerel data in the other project ("Towards improved selectivity of Atlantic mackerel and horse mackerel using scientific acoustic species identification methods"). The measured backscatter data were aggregated into probability density functions of: (1) volume backscatter at 38 kHz, (2) r(70kHz), (3) r(120kHz), and (4) r(200kHz) for each species. Data were stored at different resolutions, referred to as either individual “pixels”, “cell”, or “school” (see Figure 3). A cell was defined as 16 pings x 50 pixels vertically. The cells were extracted from selected sections of the echogram and had to be at least 50% full of fish backscatter values. Figure 6 shows relative frequency response [r(f)] values from measured data for mackerel, horse mackerel and boarfish. Figures 7 and 8 show the relationships of r(120 kHz) vs backscatter at 38 kHz (Sv38) and r(200 kHz) vs Sv38 in the training dataset for the 3 different categories “mackerel”, “horse mackerel” and “boarfish” at the resolution of entire schools. The software can then recognize fish categories with the training based on acoustic data recorded on these species.

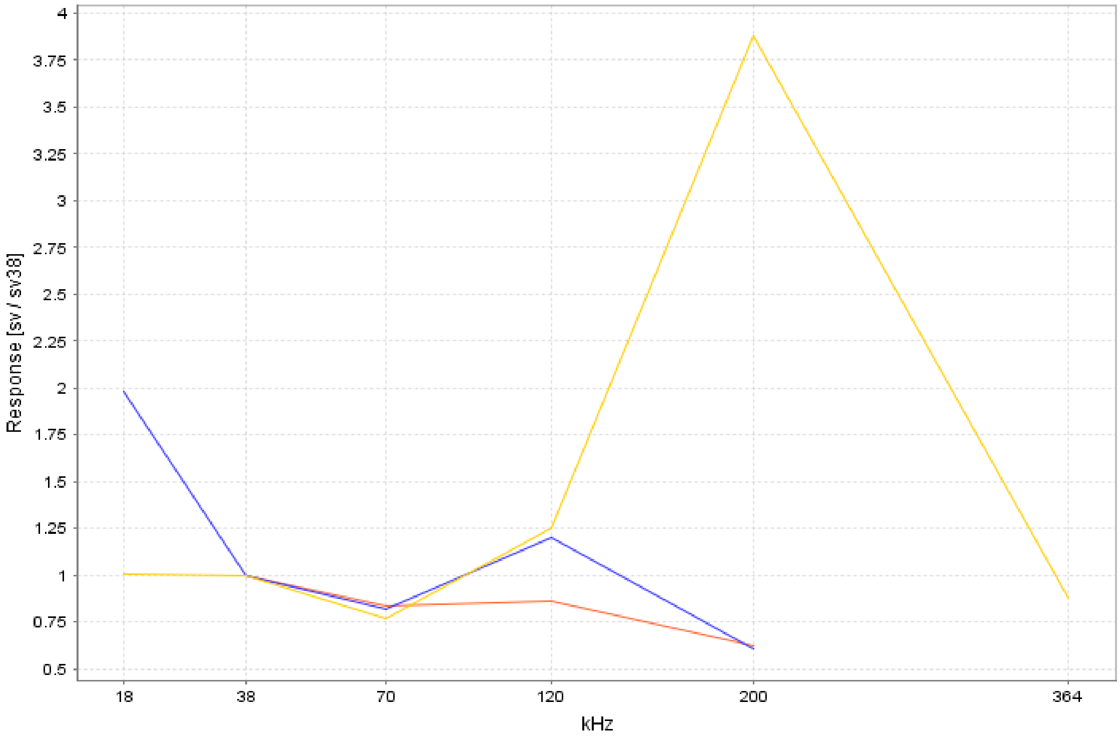


Figure 6. Relative frequency response: the measured relative echo strength per frequency for different fish species (yellow: mackerel, blue: horse mackerel, orange: boarfish)

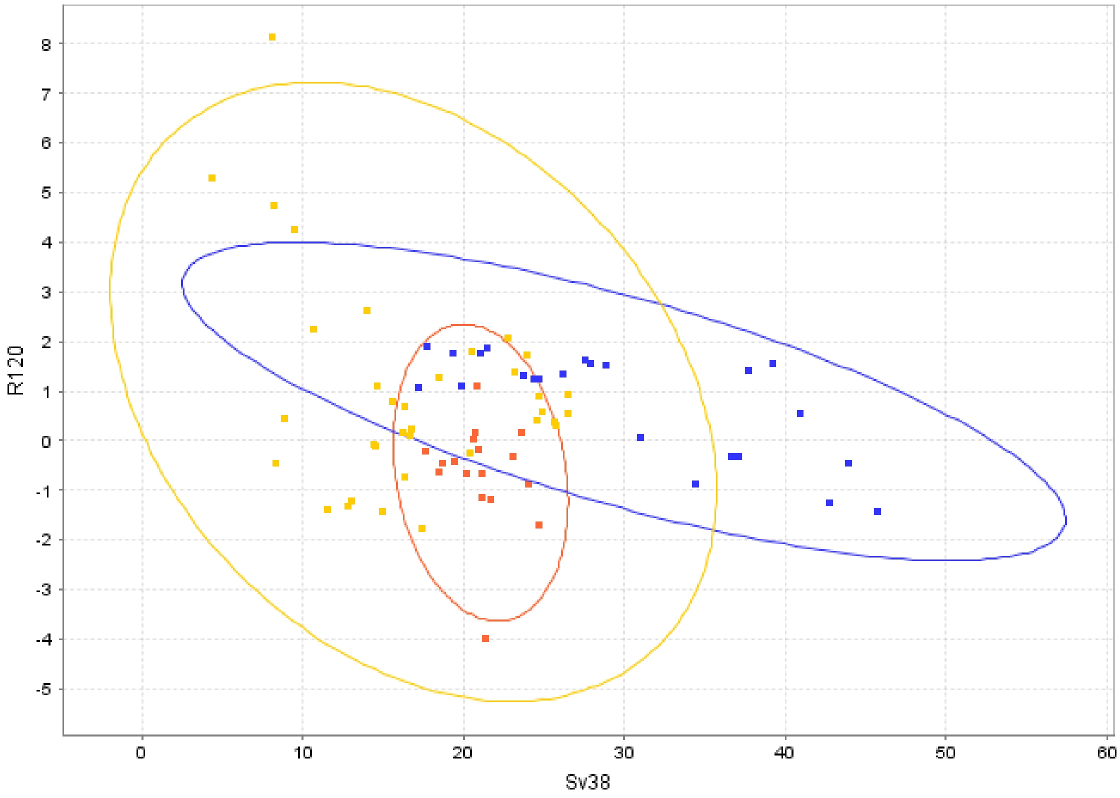


Figure 7. Relationship between the relative frequency response r(f) at 120 kHz and backscatter at 38 kHz for different fish species (yellow: mackerel, blue: horse mackerel, orange: boarfish).

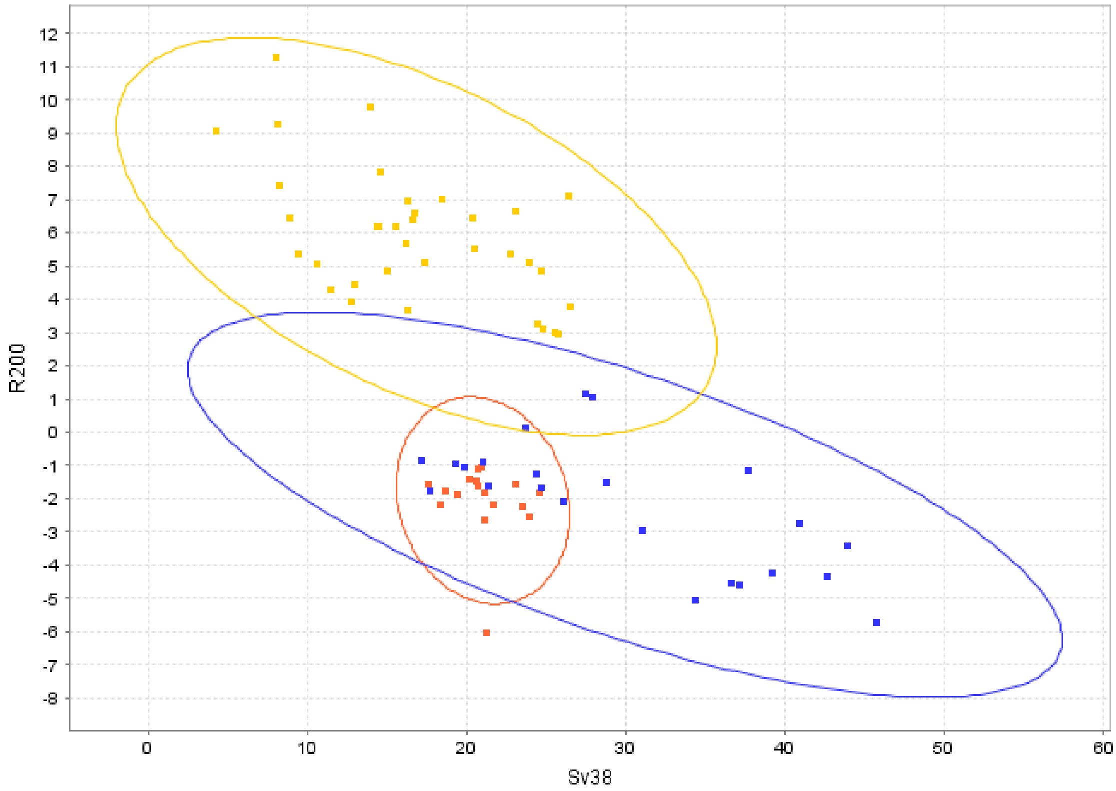


Figure 8. Relationship between the relative frequency response r(f) at 200 kHz and backscatter at 38 kHz for different fish species (yellow: mackerel, blue: horse mackerel, orange: boarfish).

From the data it is evident that the relative backscatter at 120 kHz of boarfish, including the associated variability, is similar to that of mackerel and horse mackerel. At 200 kHz, the relative backscatter of boarfish and horse mackerel is similar to each other, but more distinct to that of mackerel. Each category was represented by a Gaussian distribution for Sv(38), r(70), r(120), and r(200) with parameters estimated from the training data. A cut-off threshold corresponding to an outlier fraction of 10% restricted the acceptable part of the distributions. An example of deriving such distributions from the relative frequency response relationships and resulting classification are displayed in Figure 9. Any samples that fell outside the distributions were categorized as “no category”.

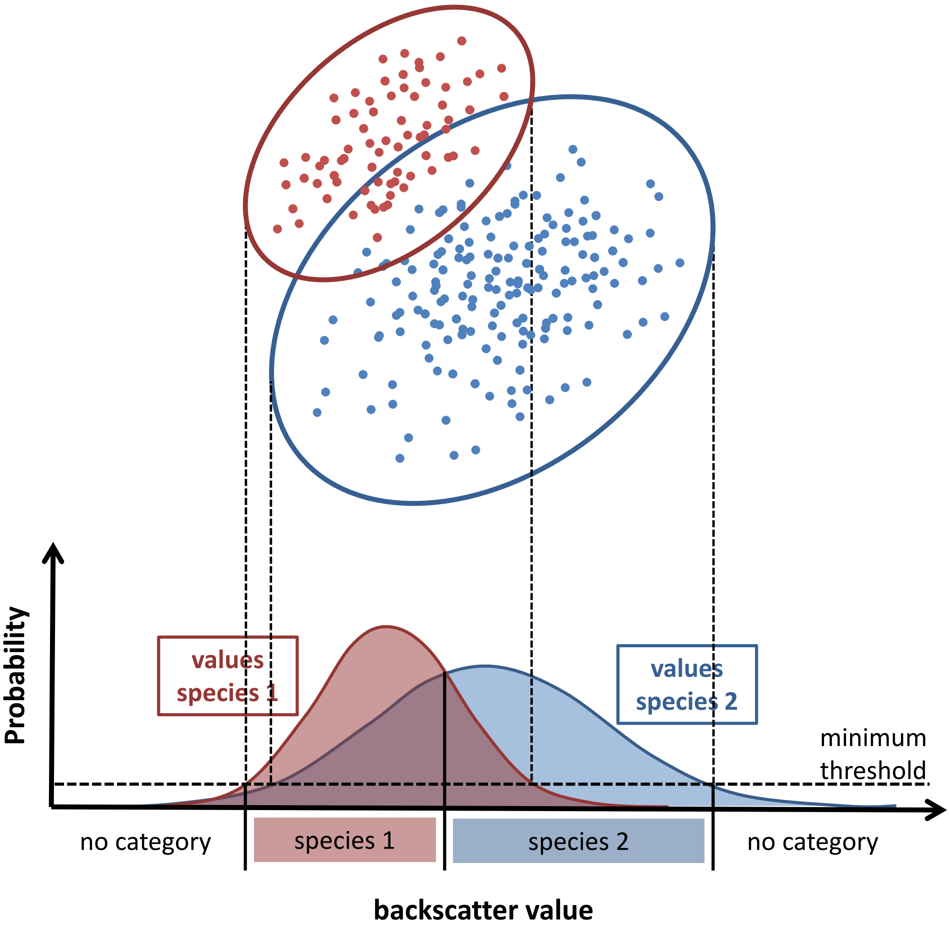


Figure 9. Example of density distributions of backscatter values for two different species and resulting classification.

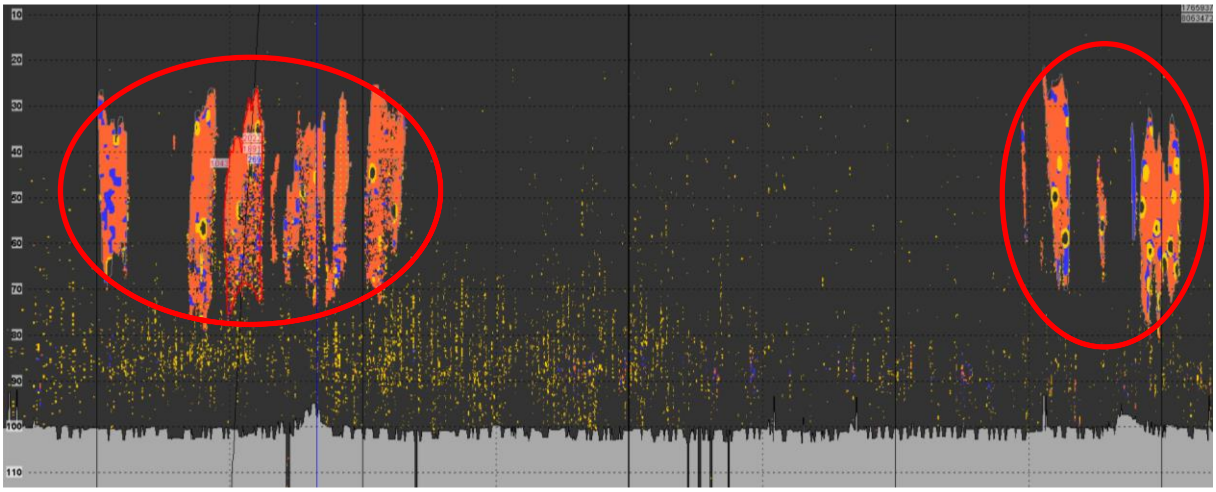


Figure 10. Colour-based classification example of identified boarfish schools in the SEAT software (shown inside the red circles).

Based on the implemented training dataset, the LSSS/SEAT software classified most of the detected boarfish schools from the collected acoustic dataset (Figure 10). However, due to the similarities, there is

still significant overlap to be expected between the classification of boarfish and especially horse mackerel. The data analysis shows that several features influence the potential for classification based on acoustic multifrequency data. The more similar a fish species scatters sound at a particular frequency compared to another fish species, the more difficult is classification. Similarly, if backscatter of a fish species at a certain frequency is very variable, chances are high that it overlaps with the backscatter features of another fish species, therefore reducing the chances for successful distinction.
Generally, it can be stated that:

The highest chance for successful species classification can be achieved by trying to characterise as few different species as possible, each of which showing large backscatter differences over as many different and wide range of single acoustic frequencies

Boarfish identification potential from multifrequency data

The dataset allows us to make some predictions about the classification potential between boarfish, mackerel and horse mackerel if the four different frequencies (38, 70, 120, and 200 kHz) are used. Based on the overlap of measured backscatter strength values at the different frequencies (Figure 11), the resulting classification potential to distinguish between all three species is poor: while most of the mackerel school cells are correctly classified (~85%), only about half (52%) of those for boarfish and 60% of the horse mackerel could be correctly classified (Figure 12). Such values will probably not result in a significant improvement of catch selectivity. However, these findings are based on a relatively low amount of boarfish data and the observed similarities between these species at the applied frequencies.

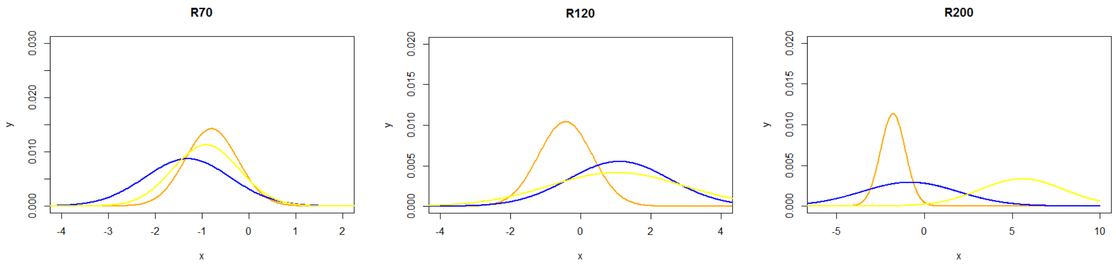
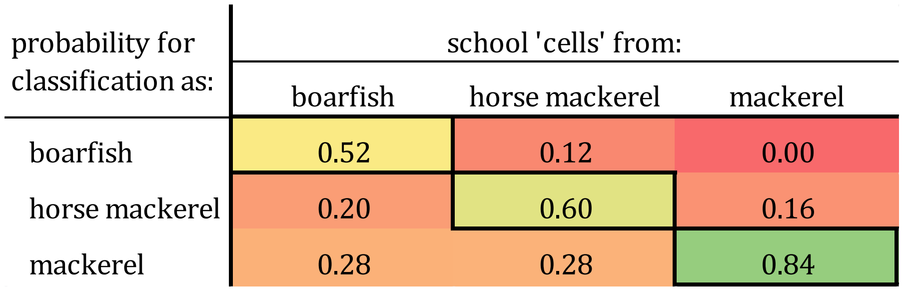


Figure 11. Distributions of relative frequency response values at 70 kHz (left), 120 kHz (middle), and 200 kHz (right) for school 'cells' of mackerel (yellow), horse mackerel (blue), and boarfish (orange).

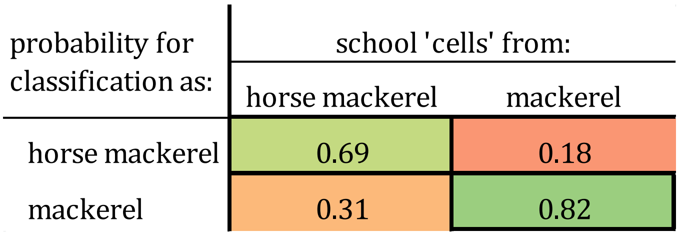


probability for classification as:	school 'cells' from:		
	boarfish	horse mackerel	mackerel
boarfish	0.52	0.12	0.00
horse mackerel	0.20	0.60	0.16
mackerel	0.28	0.28	0.84

Figure 12. Probability for correct classification of mackerel, horse mackerel and boarfish school cells based on acoustic multifrequency data (38, 70, 120, and 200 kHz).

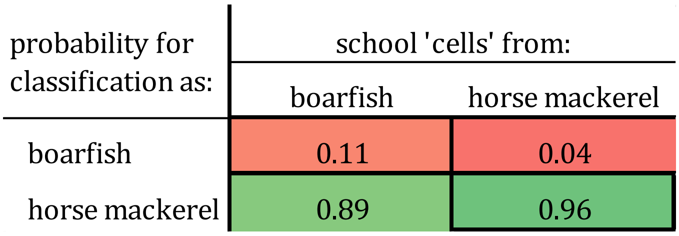
To illustrate this issue better, the same analysis was done for just two species: mackerel and horse mackerel. Due to the increased differences in backscatter between these species at the given frequencies, a majority of the identified cells within schools (70-80%) can also be expected to be correctly classified (Figure 13). Therefore, the potential to increase selectivity is higher. Similar results could be expected when just comparing the two species boarfish and mackerel, due to the given differences in frequency-specific backscatter. On the other hand, if the comparison is just between boarfish and horse mackerel, a significant part of boarfish schools (~90%) would be wrongly classified as horse mackerel, while most horse mackerel school cells (96%) would receive the correct classification (Figure 14). This is primarily due to the different amounts of data available for these two species. Compared to horse mackerel, for boarfish there was only information from a few schools available. Therefore, the conclusions we can make from these in terms of backscatter characteristics are limited to a narrow range of observations. This is reflected by the narrower distributions of relative frequency response values for boarfish (Figure 11). At the observed frequencies, the differences between boarfish and horse mackerel were most prominent at 120 kHz. If that difference could be confirmed with more data (in the future), the “weight” allocated to boarfish would increase and therefore may lead to an improved distinction of the two species.

Consequently, just trying to classify only two species instead of all three together does not automatically lead to better results. The classification will be easier if the two species are acoustically quite different (*e.g.* mackerel/horse mackerel or mackerel/boarfish), but difficulties still remain if the two species are acoustically similar (e.g. horse mackerel/boarfish).



probability for classification as:	school 'cells' from:	
	horse mackerel	mackerel
horse mackerel	0.69	0.18
mackerel	0.31	0.82

Figure 13. Probability for correct classification of mackerel and horse mackerel school cells based on acoustic multifrequency data (38, 70, 120, and 200 kHz).



probability for classification as:	school 'cells' from:	
	boarfish	horse mackerel
boarfish	0.11	0.04
horse mackerel	0.89	0.96

Figure 14. Probability for correct classification of boarfish and horse mackerel school cells based on acoustic multifrequency data (38, 70, 120, and 200 kHz).

4. Conclusions

Acoustic properties of boarfish at the most advanced multifrequency setup used in the PFA fleet at the time of the study (38, 70, 120, and 200 kHz –available on SCH6 'Alida' & SCH72 'Frank Bonefaas') are similar as those of horse mackerel. The properties of mackerel differs from both these species.
Consequently, distinction between either 'horse mackerel & mackerel' OR 'boarfish & mackerel' using the four frequencies has a high potential for success. However, if all three species are taken together, the identification of either horse mackerel and boarfish is "blurred" due to their similarities. Bad classification results are also expected if just boarfish and horse mackerel are compared with each other, due to their acoustic similarities.

Due to the opportunistic nature of the available boarfish data (collected during a dedicated fishery on mackerel and horse mackerel), the amount of available data for boarfish was less than for the other two species, both in terms of available schools (segments) and observed situations (time period & area):

	boarfish	horse mackerel	mackerel
whole schools	17	23	24
school 'cells'	143	539	303
situations (area/time)	2	16	10

Consequently the boarfish scatter data showed less variability (see Figure 11), as they came from limited amounts of schools from a nearly identical area and time period. Collecting more (diverse) data on boarfish would lead to more representative results. However, that could also mean ending up with more variability, leading to worse conclusions about the classification potential between these three species.

Potential improvement of classification success between the three species may be achieved by:

(1) Adding more single frequencies at which the three species may show differences in backscatter (e.g. 18 or 333 kHz)
(2) Using broadband/wideband data that reveal the scatter response over many more frequencies, therefore improving the chances for successful classification

5. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

Report : C137/14
Project Number : 4301502101

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Ben Scoulding
Scientist

In the absence,

Drs. J.H.M. Schobben
Head of Fish Department

Signature:

Date: 24/06/2015

Approved: Dr. ir. N.A. Steins
Head of Fisheries Department

Signature:

Date: 24/06/2015

Appendix A. Literature review on pelagic fishing, fish behaviour and selectivity enhancing techniques.

Characteristics of pelagic fishing

In pelagic or midwater trawling the gear is towed between the sea floor and the sea surface. The position of the gear follows from the quasi-static equilibrium of hydrodynamic and gravitational forces determined by the dimensions and drag of the rigging (length of warps, size type and rigging of otterboards, length of bridles, bridle weights), the net drag and the towing speed (de Boer and Van der Meulen, 1976). The main target species in this fishery are: herring (*Clupea harengus* L.), Atlantic mackerel (*Scomber scombrus* L.), horse mackerel (*Trachurus trachurus* L.), blue whiting (*Micromesistius poutassou* R.), sardinella (*Sardinella spp.* L.), etc..

The Dutch pelagic freezer trawler fleet consists of a small number of large vessels at present, approximately 12. Haul duration is very variable and dependent upon catch size. The towing speed of the pelagic trawls is around 5 knots. In most cases fish is not gutting but sorted mechanically and frozen in plate freezers after intermediate storage in sea water circulated cooling buffer tanks and then packed in carton boxes and stored in a freezing hold.

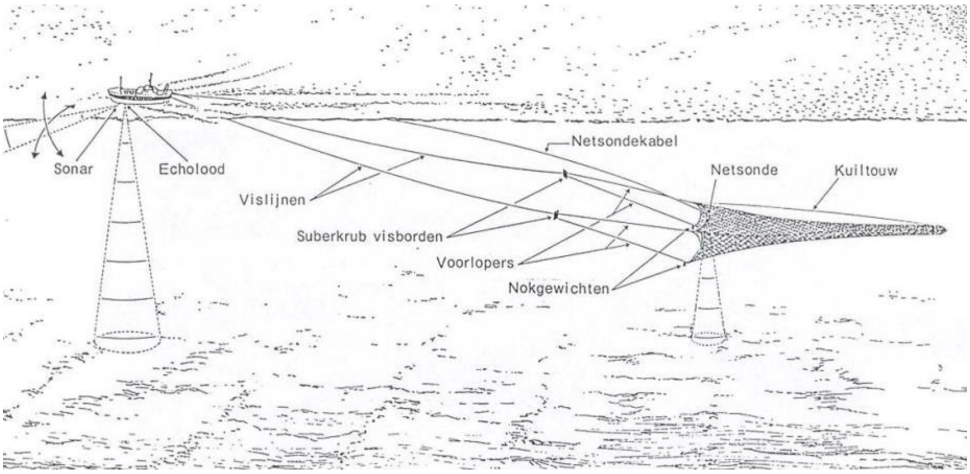
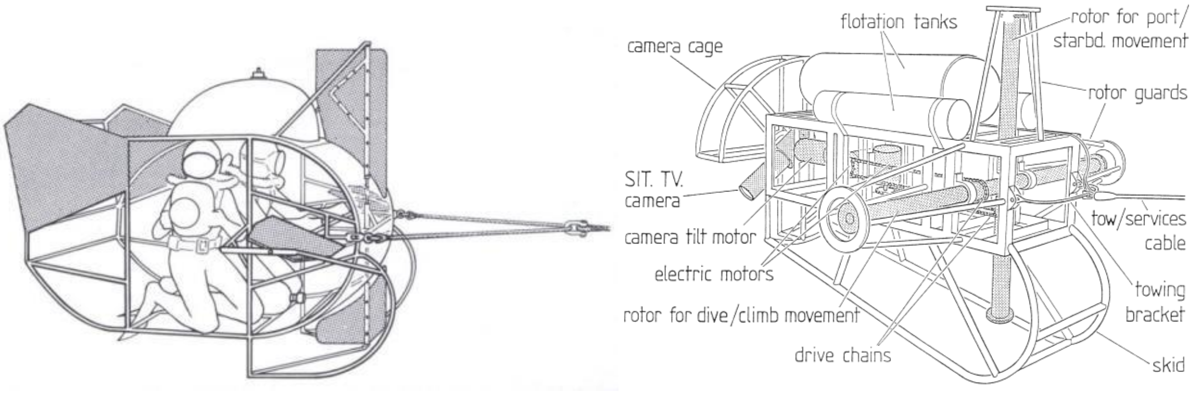


Figure 1. Pelagic trawl (from: E.J. de Boer and C. Vermeulen, 1976)

Observation techniques

Knowledge of fish behaviour in fishing gears followed from direct observation using underwater cameras. As early as in the 1950s divers made underwater observations of fishing gears, by letting the net pass or being towed with the net. This work was dangerous due to diving gear (oxygen supply hoses) being subject to the relatively high speed water flow making handling strenuous. Because of decompression and to avoid caisson illness the observation duration and depths were limited An example of a suitable working area is the Scottish Moray Firth (with depths to 20 m). To ease work a so-called towed manned vehicle has been developed in the 1970s. One of two divers could operate the vehicle and the other handle the camera (Main and Sangster, 1978; Main and Sangster, 1983) and Figure 2a. The vehicle is towed behind the fishing vessel and a rubber boat was also used with a stand-by diver to assist in case of emergencies. Such an operation required an adequate communication between the three crafts (vehicle, inflatable and trawler). Using this technique enabled many underwater footage from which major behavioural characteristics could be deducted. The drawback of limited observation time and depth remained, though.

For this reason a new class of observation platforms was developed in the 1980s at the Marine Laboratory of Aberdeen, Scotland the ROV (Remotely Controlled Vehicle) (Priestley et al., 1985), Figure 2b. This device could be positioned toward the gear by using so-called "Magnus” rotors, revolving cylinders with which a cross-force to the flow direction could be generated, depending on speed of rotation (r.p.m.). The cylinders were placed in a cross to enable a force down and up and sideways. The ROV is also towed by the vessel and could manoeuvre around a fishing gear within certain limitations in depth and sideways. A major advantage is that without the presence of humans both the observation time had no limitations and the depth range could be extended considerably. With very light sensitive cameras (e.g. type S.I.T) footage could be taken from fishing grounds as deep as 100 m. In 1985 IMARES (former RIVO) purchased such an ROV. In the years between 1985 and 1993 various observations were made of large pelagic trawls. The device had been redesigned and improved using CCTV cameras, but unfortunately maintenance costs were very high and the equipment not kept operational long since. A fine summary of fishing gear technology and development of observation equipment is given in Walsh et al. (2002).



(a) (b)

Figure 2. Towed vehicles for direct observation developed at the Marine Lab Aberdeen (now Marine Science Scotland), manned (a) and unmanned using rotors (b)

Another device that can be used for direct observation is the ‘acoustic’ camera, the DIDSON, a high frequency multi-beam sonar with which fish reactions can also be visualized. Using special software for analysis quantitative data can be generated concerning fish in the trawl path and the percentage caught by a gear, as well as the type of reactions.

Recently the “Deep vision” stereo camera system was developed which enables visualisation of fish reactions inside a net and the simultaneous storage of operational data (latitude, longitude, depth, time). These data can be integrated with echograms in echo-surveys and organisms with a length range of 1-70 cm detected. Such a device can be used to avoid unwanted catches or filter specimen out in an active manner (Rosen and Holst, 2013), Figure 3 and Figure 4.

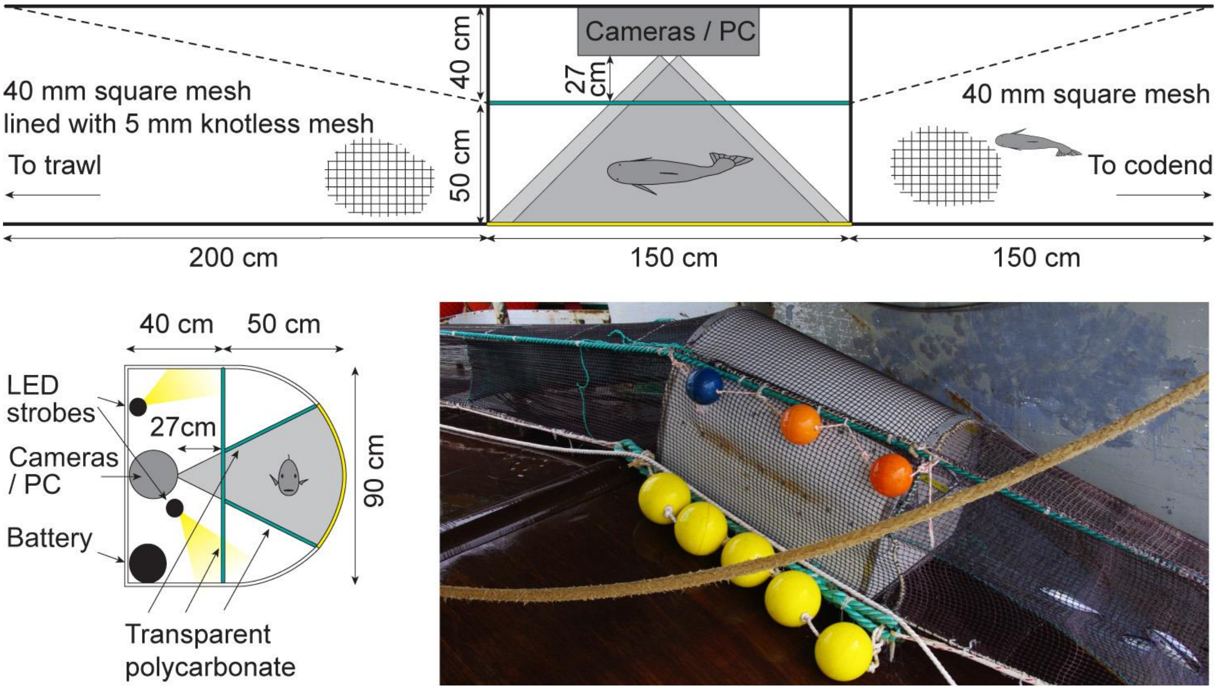


Figure 3. "Deep Vision" in a trawl section with camera, seen from above, from aside and in a photo (Rosen and Holst, 2013).

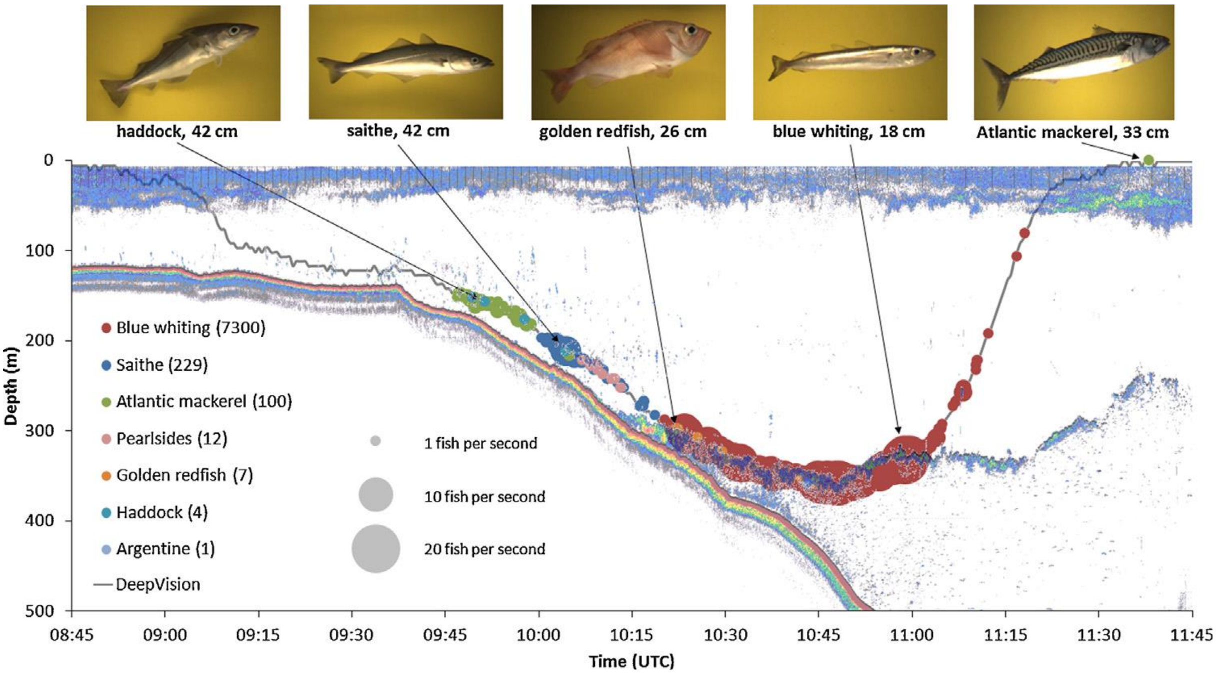


Figure 4. Echogram with fish marks and counts per second, with integrated "Deep vision" images added (Rosen and Holst, 2013).

General patterns of behaviour

Fish behaviour is determined by a combination of acoustic, visual and tactile stimuli, generated by the fishing vessel and her gear. Many fish species have excellent hearing capabilities (Popper and Hastings, 2009), and reactions of fish to sound stimuli were documented in many studies (van Marlen et al., 1997). The effect of underwater radiated noise is recognised in acoustic surveys, and led to strict requirements on the level of sound emitted by research vessels (ICES, 1995). Nevertheless, the general reaction pattern to fishing gears seems to be dominated by visual stimuli. Observations in extreme dark conditions (lower than 10^{-6} lux) showed that fish did not react unless physical contact took place (Glass and Wardle, 1989). In most cases underwater light levels are high enough for fish to detect approaching gear. Sound stimuli increase the level of alertness, but additional stimuli are apparently needed to invoke a reaction.

Opto-motoric reflex

If we assume that a towed gear, consisting of warps, otterboards, sweeps, and the net itself is approaching fish in a stationary position, at some moment they become aware of the moving components, starting with the otterboards, and the sand clouds usually generated by these. The fish react by keeping a distance away from these moving obstacles and usually swim around them (Figure 7). Between the otterboards the fish are guided by the visual stimuli of boards and sand clouds until they come in the vicinity of the net mouth. At some point they turn and start swimming along with the moving gear (Figure 9). This reaction is called opto-motoric reflex and is crucial for understanding the general pattern of behaviour. It means that fish are not just taken over by the trawl and sifted through its meshes, but move along with the gear some period during the capture process. Many observations show that fish swim along apparently without any notion of danger in parts of the gear where escape through large holes would be easy. The turning reaction also depends on visibility, when the water is clear and light conditions favourable the fish may detect the trawl at great distances and move out of its path. In conditions of poor visibility the fish may not detect the net until they are close to or in the net mouth. The system of cables running from the doors to the wings of the net can cause fish to react. A cable running over the sea bed at an angle is detected by groundfish buried in the sediment. It causes a jumping reaction perpendicular to it and moving away from it, after which these fish often seek shelter within the sediment, where some time later they are confronted with the moving cable again. This reaction is usually repeated several times which result in the fish being guided in the direction of the net mouth. The sweeps are herding the fish in the trawl path towards the net mouth where they turn and swim along (Figure 8). Depending on the swimming abilities and the towing speed this phase may be of considerable duration and determines whether the fish are caught at all (Figure 11). The swimming capabilities depend on species, body length and temperature (Figure 13). When getting exhaust the swimming pattern changes to leap forward following by dropping back further into the net, where chances of escape are determined by the codend meshes in relation to morphology and cross sectional dimensions (Figure 12). Often fish are pressed against the meshes of the codend in the water flow or washed throughout the codend due to the flow being turbulent by movements of the vessel and gear. Not all meshes in a codend offer a potential escape route. Due to its mechanical properties and the presence of fish the geometry alters during a tow into a bulbous shape, with many meshes constricted and other widely opened. This led to the idea of changing its construction in such a way, that more meshes remain open and offer escape possibilities for juvenile fish, e.g. the square mesh concept. More specifically this will be dealt with in the next lecture.

Most trawls owe their catching ability from the opto-motoric reflex. Only in a small part (i.e. the codend) the mesh size is suitable for retaining fish. Meshes of extreme sizes (up to 256 m in large pelagic trawls) were shown to herd fish into the codend without escape. Views differ whether the visual stimuli or vibrations of these twines detected by the lateral line dominate the reaction. The principle of herding by cables or ropes is known since many years and already applied in herring trawls of relatively small dimensions, that were fitted with a system of ropes kept up by a kite (called 'herring-patent').

Swimming characteristics

The swimming abilities of many species were extensively investigated (Ref 16, Ref 17). The maximum attainable swimming speed is about 10 body lengths per second, decreasing rapidly with lower temperatures. Figure 12 shows that a cod with a body length of 35 cm is able to escape at a towing speed of 2.5 knots and a water temperature of 8-12 ºC, but no longer at 2 ºC when the speed is raised to 3.5 knots.

Behavioural characteristics of fish in contact with fishing gears were observed with divers and underwater cameras (Graham et al., 2004; Main and Sangster, 1978; Main and Sangster, 1981; Main and Sangster, 1983). A detailed description of fish behaviour inside trawl nets is given in (Wardle, 1993).

Fish behaviour is determined by a combination of acoustical, visual and other stimuli (e.g. vibrations) generated by the fishing gear moving through the water. Research showed that many fish species are able to detect sound well and that they react to an approaching vessel and gear (Anonymous, 2012; Hastings and Popper, 2005; Popper and Hastings, 2009). This is especially relevant for acoustic surveys of pelagic fish species such as herring (*Clupea harengus* L.) (Vabø et al., 2002). Extended measurements were done on the sound emitted under water by various fisheries research vessels, and this has led to recommendations on underwater sound levels produced by such vessels (ICES, 1995; Peña et al., 2011). These requirements are incorporated in recent designs of fisheries research vessels. Although sound stimuli play a role fish reactions to fishing gears seem to be dominated by visual stimuli. Observations at extreme dark conditions (in northern fishing grounds in wintertime with deck lights switched off, with light levels lower than 10^{-6} lux) showed that fish are taken by surprise in all sorts of orientations by approaching gear components, without showing the usual opto-motor response (Glass and Wardle, 1989). In most cases the ambient light levels are high enough for most species to detect approaching fishing gear. Sound stimuli seem to raise awareness, but visual stimuli are needed in addition to elicit a response.

Considering a trawl gear, the first component that fish encounter is likely one of the otterboards. Fish tend to stay away and swim around such objects as though they are large predators depending on visibility and the presence of a sound cloud (in the case of bottom trawls, see Figure 9). Between both otterboards fish are guided to the net mouth by the visual stimuli of boards and sand clouds. At some point in front of the net mouth the fish turn and start swimming along with the moving trawl in the direction of motion (Figure 10a). When visibility is good the fish may see the approaching net mouth and turn, at lower visibility turning might happen when the fish are already inside the net mouth or futher down the net. This swimming along moving components is often referred to as **'opto-motor response**'. Another type of response is the **'erratic response**' that is irregular and unpredictable with large variations in swimming speed, acceleration and direction (Kim and Wardle, 2003). The opto-motor response forms the basis of catch efficiency of trawl nets, together with the retention by the meshes in the codend. When these are large enough in relation to the size of the fish a probable outcome is escape through the meshes (Kim and Wardle, 2003) and Figure 5.

Fish can swim along with the net until fatigue sets in, depending on swimming endurance and towing speed (Figure 12a). Swimming endurance is a function of species, length and water temperature (Figure 12b). We have seen fish schools swimming in front of large escape opening but remaining inside the net without the notion of being able to swim out. In some cases fish even swam out and returned inside the net to maintain position in a school (van Marlen, 1995; van Marlen et al., 1994).

When fish are tiring they usually turn and swim toward the codend, where they may show escape attempts. Often the fish are pressed against the netting by the water flow and remain passive (Figure 11).

The fish accumulated against the back of the codend cause the water flow to be turbulent, thus enabling some escape through meshes that are opened wide in this part of the codend, whereas meshes in the forward part are closed by the drag of the codend. Next to mesh size mesh shape is another important variable determining escape opportunities. So-called 'square meshes' (meshes hung on the square, turned 45°) offer better escape openings especially for round fish along a greater length of a codend (Robertson, 1986; Robertson and Stewart, 1988).

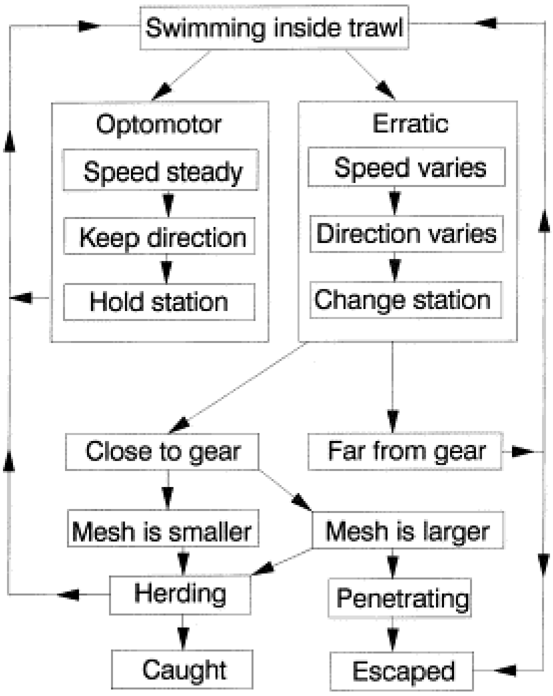


Figure 5. Fish reactions in a trawl net, from (Kim and Wardle, 2003)

In most parts of the trawl meshes are so large that escape would be easy. In spite of this fish often remain swimming inside along with the moving the net at some distance away from the netting. This is the reason that even very large meshes (even up to 256 m) can herd fish inside pelagic nets (Figure 7).

This happens also in relative dark conditions, as low light levels are already high enough for visual detection. Vision alone is not the only stimulus. In pelagic nets with large mouth openings (e.g. 100 x 50 m) fish are also herded by vibrations. This has been known for a long time. In the 1960s the so-called 'herring patent', a system of guiding ropes held up with kites, was already used to enhance the capture of herring in low opening bottom trawls. Water movements and vibrations can be picked up by the lateral line organ of pelagic fish (Schellart and Wubbels, 1998). A recent laboratory study revealed that the inner ear and the lateral line play a role in determining the direction of incoming sound and the flight reaction in gold fish (*Carassius auratus* L.) (Mirjany et al., 2011). Both the ear and the lateral line system are used in detecting and localising various types of sound stimuli for this species (Higgs and Radford, 2013).

The catching efficiency of rope trawls in which the forward netting panels are replaced by more or less parallel ropes (Figure 6a) was lower than in trawls with large conventional diamond or hexagonal meshes, indicating that some sort of cross connection generating vibrations in the water is apparently needed (Figure 6b and Figure 7, (van Marlen, 1989)).

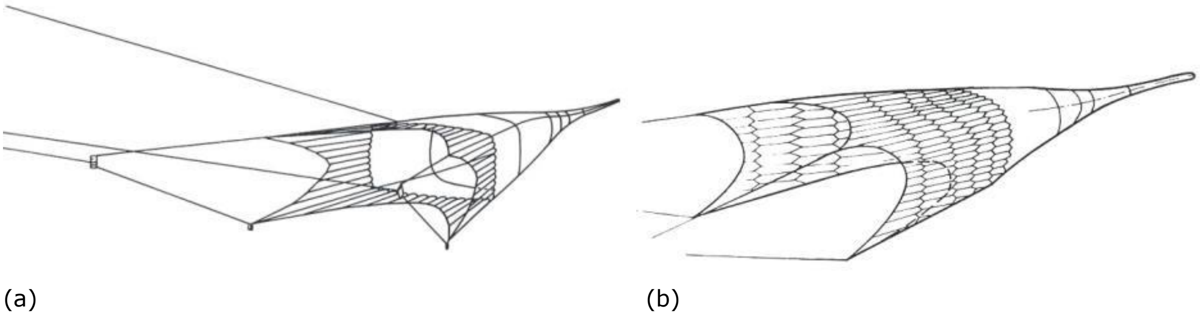

(a) (b)

Figure 6. Examples of innovative pelagic trawls. Rope trawl IFR-Rostock, GDR (a), Hexagonal mesh trawl IFR-Rostock, GDR (b)

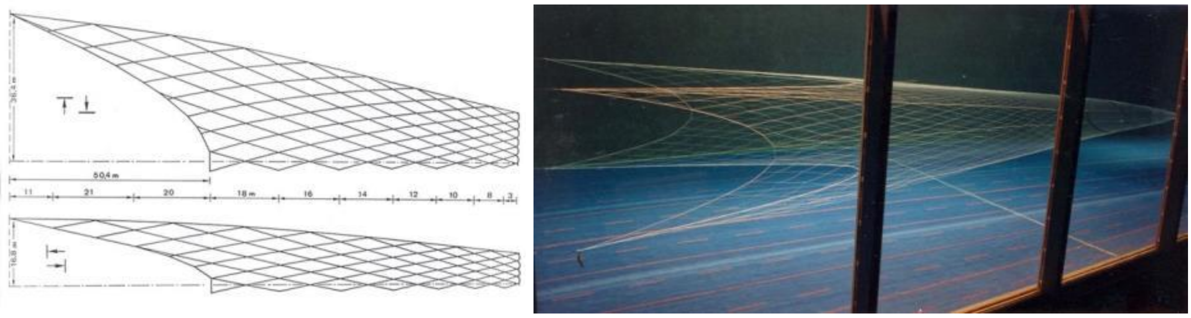


Figure 7. Pelagic trawl design with very large diamond meshes in the front part (van Marlen, 1989)

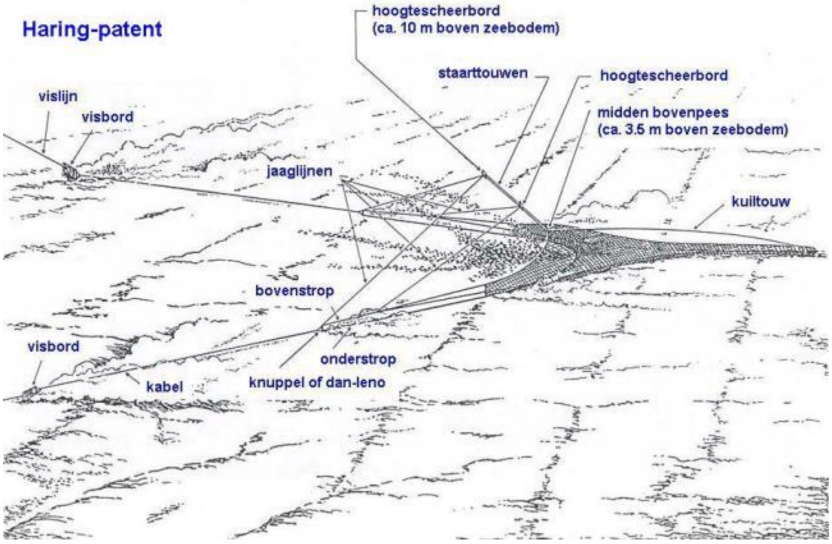


Figure 8. 'Herring-patent', bottom trawl with guiding ropes held up with kites (From: E.J. de Boer and C. van der Meulen, 1976)

Swimming speed was studied in many species (Kim and Wardle, 2003; Wardle, 1989; Wardle, 1993). The maximum value turned out to be about 10 body lengths per second. Water temperature has a pronounced effect. The maximum speed of cod (*Gadus morhua* L.) is reduced to 50% when temperature was lowered to 10 ºC, which also diminishes escape possibilities.

Figure 12b shows that a cod of 35 cm length can escape with a towing speed of 2.5 knots and a water temperature of 8-12 ºC, but no longer at 2 ºC or a speed of 3.5 knots.

Experiments with fish in a circular tank showed that they can maintain certain swimming speeds a long time. This is called 'sustained speed'. When forced to swim at higher speeds fatigue occurs (at 'prolonged speeds') followed by irregular leaps forward called 'burst swimming' (Figure 12). Species, water temperature and fish length determine the endurance speed (Wardle, 1993). This speed in relation to the towing speed of a trawl net determine how long fish can swim along inside a net (Figure 12).

It can take a considerable amount of time before fish are tired and enter the aft part of a net. Sometimes fish are still swimming along in the middle body of the net and swim forward out during hauling when the towing speed is reduced (Misund and Haugland, 2011). A good skipper knows how to avoid this from happening. Fish accumulating in the codend cause it to swirl around in a turbulent flow (Figure 11). Those specimen entering last into the codend can still be in a relatively good condition, but fish that are pressed against the meshes from the early phases of a haul will be worse off. Tow duration has a great influence on fish condition and may vary with fishing technique. Usually a codend is filled gradually with time, and the layer of fish pressed against the rear of the codend can help those entering later to have better escape possibilities. The narrowing shape of a net toward the rear can create crowding of fish inside the net and evoke escape attempts, often resulting in gilled fish in front of the codend. Baltic herring was seen to swim upward in day light when a trawl was approaching, and juveniles showed escape reactions in dark conditions at the upper panel in the aft part (Suuronen et al., 1997).

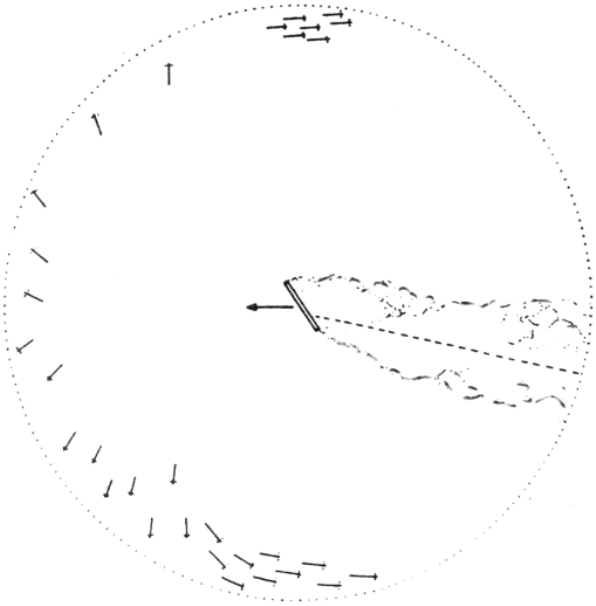
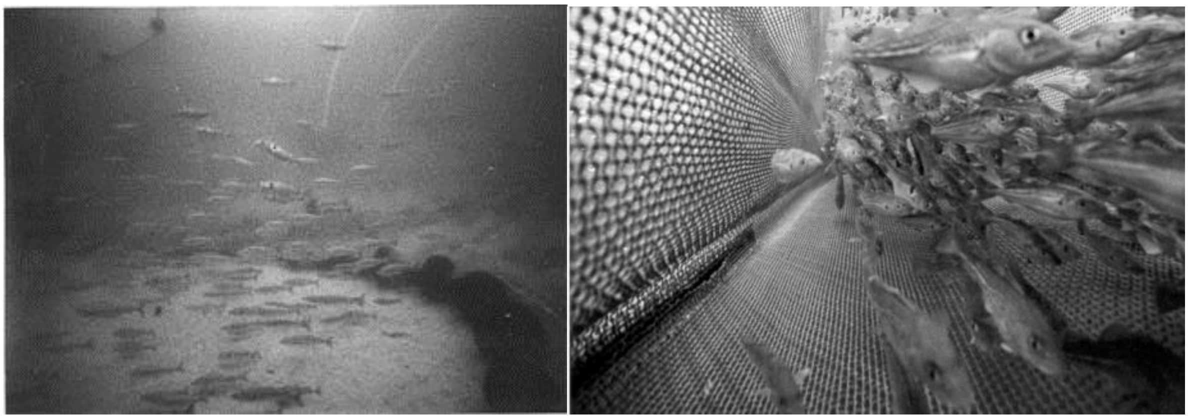


Figure 9. Fish behaviour around an otter board



(a) (b)

Figure 10. Fish behaviour in the net mouth of a bottom trawl (a) and inside a net (b), opto-motor response

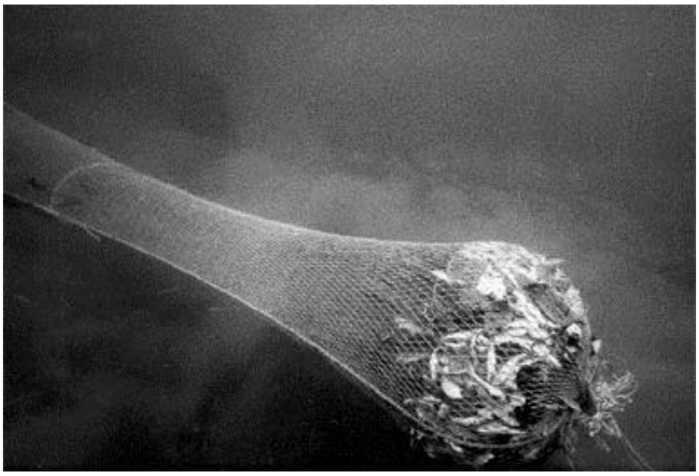
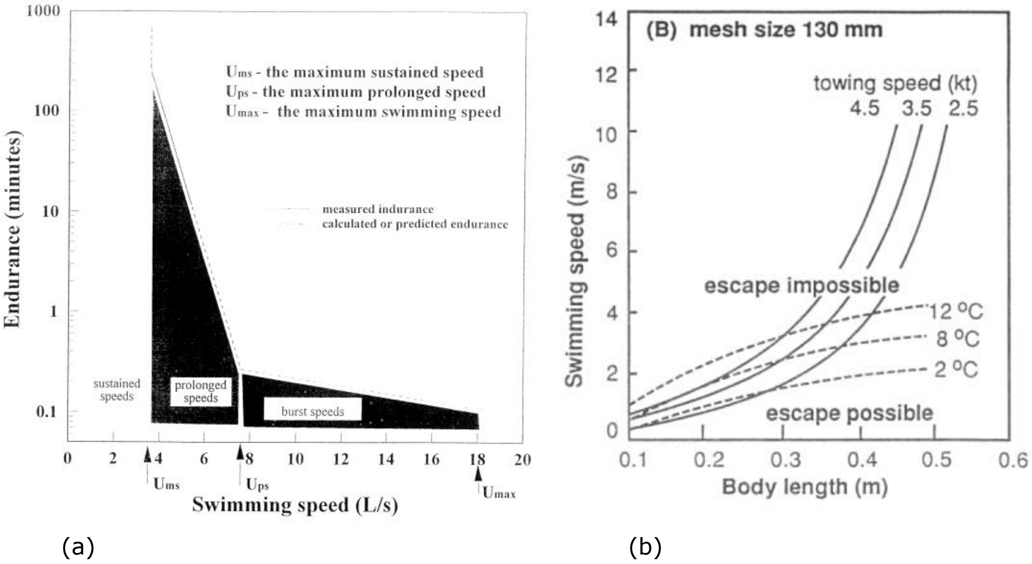


Figure 11. Fish behaviour in a codend



(a) (b)

Figure 12. Swimming endurance as a function of swimming speed in body lengths per second (a) and escape possibilities in relation yo body length and swimming speed (b)

Pelagic fish species often show schooling behaviour. Individuals are protected from predation by swimming in large groups, rendering individual fish more difficult to detect. Such behaviour was demonstrated in trials in the circular tank of the Marine Laboratory of Aberdeen, Scotland (Figure 13).

In the 1990s experiments were conducted to investigate the possibility of using differing behavioural patterns inside pelagic trawls to separate Atlantic mackerel (*Scomber scombrus* L.), from horse mackerel (*Trachurus trachurus* L.) and herring. The study showed that when herded inside a trawl these species mingle in one school hampering separation, although schools swam apart outside the trawl (van Marlen, 1995; van Marlen et al., 1994).

Sardinella (*Sardinella maderensis* and *Sardinella aurita*) observed in African coastal waters near Angola showed two distinct types of reaction: a 'fright'-reaction, in which schools disperse within seconds and individuals swam away in different directions, and an 'adjust'-reaction, in which a school kept clustered and swam along with the net for longer time (10-60 min). Heaving in with reduced speed caused such schools to swim forward inside the net (Misund and Haugland, 2011).

Figure 13. Schooling behaviour of horse mackerel (from Wardle, 1993)

In pelagic trawling it can happen that a large bulk of fish enter the net at once. Such a situation can reduce escape opportunities for individual unwanted juvenile fish through a 'sorting grid' blocking more or less their passage; see Figure 14 and Figure 17 and (O'Neill et al., 2008).

This was observed with underwater cameras. Some sort of guidance of fish to encounter the openings between the bars of a sorting grid may therefore be needed to enhance escape attempts (van Marlen, 1995; van Marlen et al., 1994), Figure 15 and Figure 16, showing a codend with a cover.

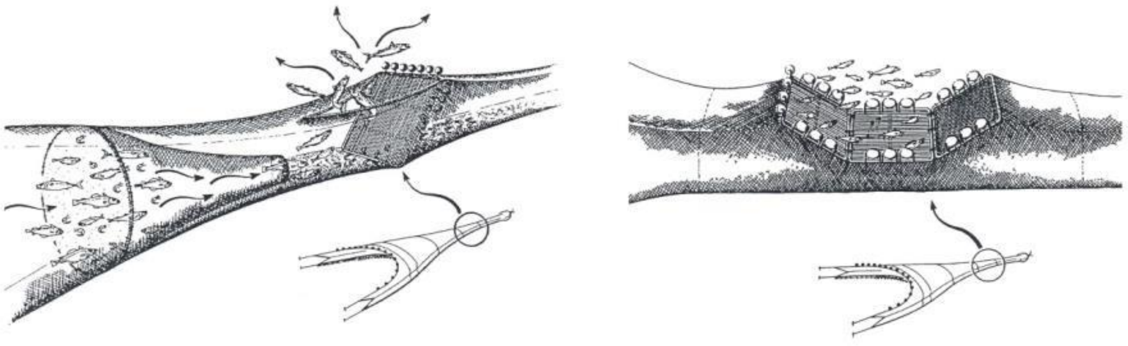

(a) (b)

Figure 14. Sorting grids, type "Nordmøre" (a) and "Sort-X" (b)

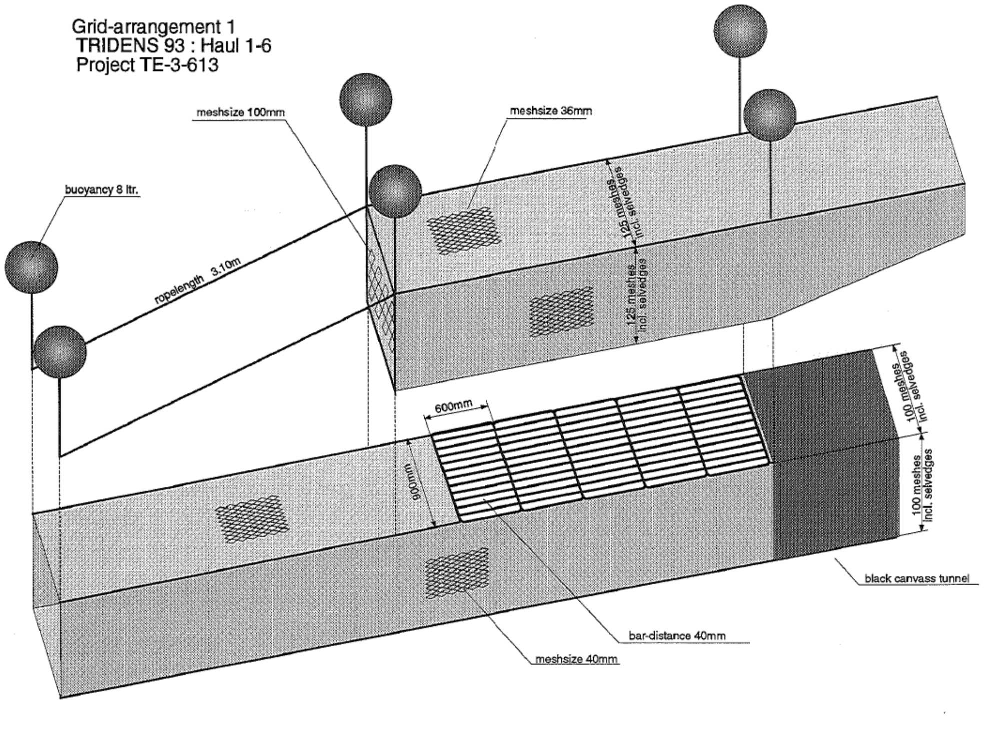


Figure 15. Example of a sorting grid configuration tested in project SELMITRA in 1993 (van Marlen et al., 1994)

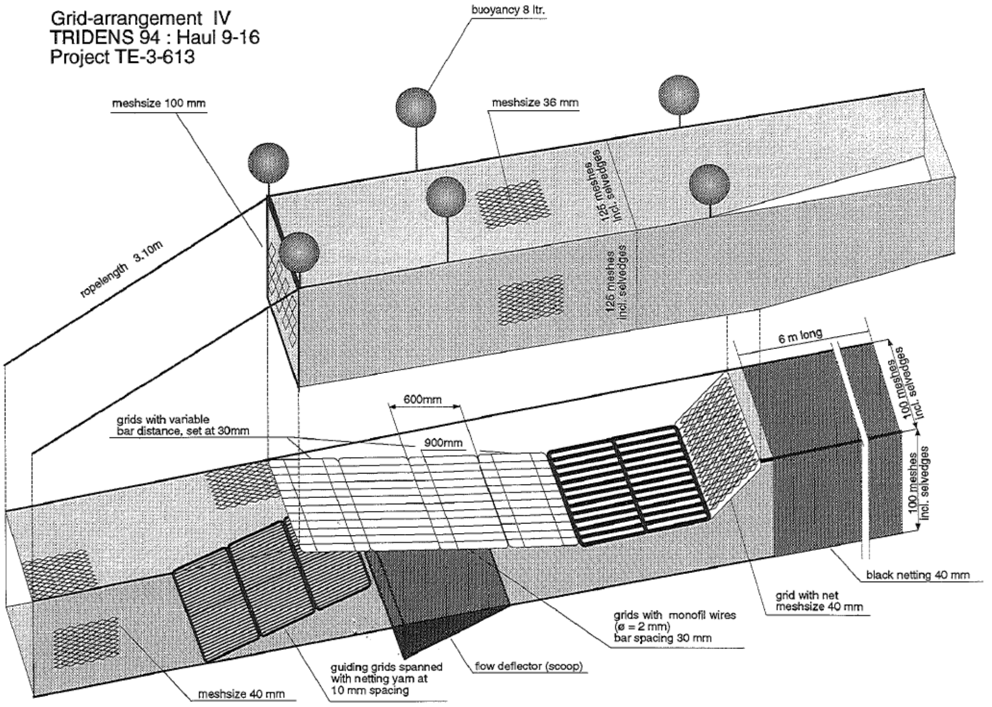
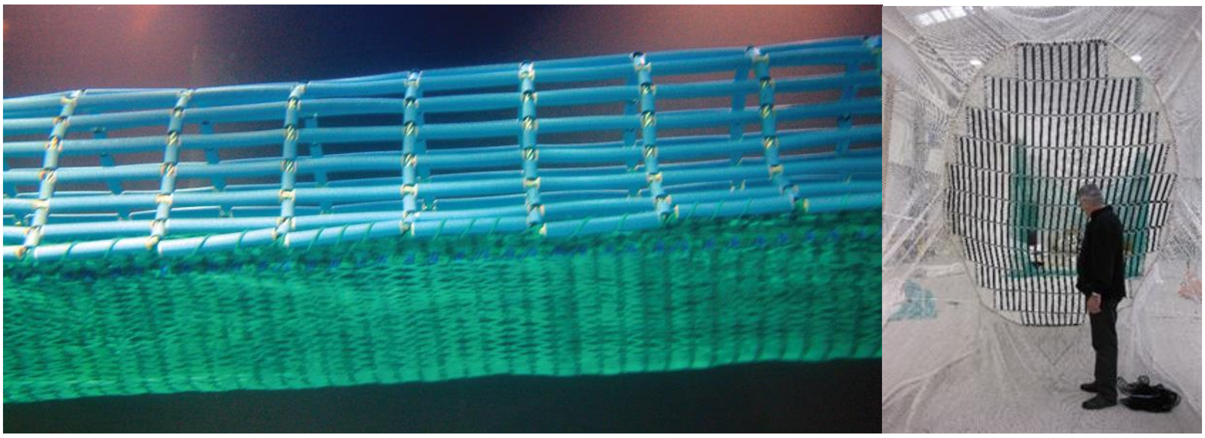


Figure 16. Example of a sorting grid configuration tested in project SELMITRA in 1994 (van Marlen, 1995)



(a) (b)

Figure 17. 'Flexi-grid' in upper panel (a), in the tunnel type Vónin (b)

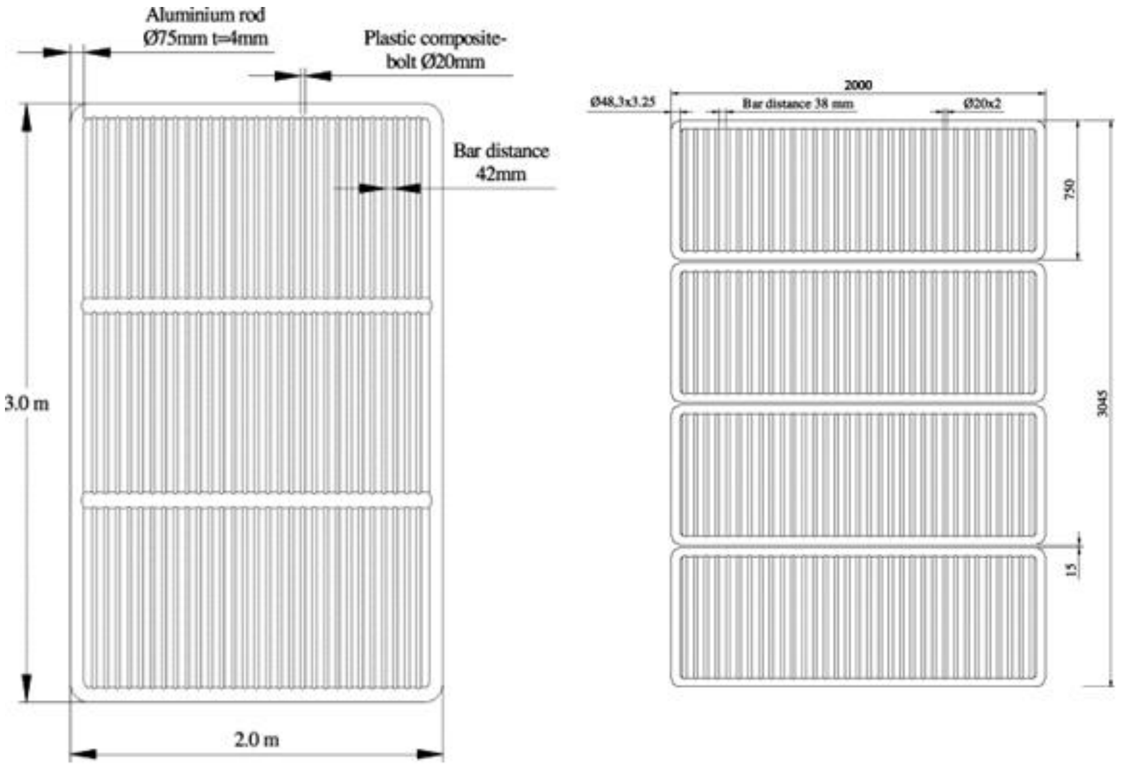


Figure 18. Typical sorting grid dimensions

Sorting grids were tested in the Norwegian fishery on Atlantic mackerel in 1997-1999 with good results at large catch volumes. Length selectivity could raise income from 8 to 18% (Kvalsvik et al., 2002). Figure 18 depicts the dimensions and shape of these grids. Grids were also tried in Portuguese bottom trawling to decrease bycatches of juvenile undersized fish showing differences in reactions between hake (*Merluccius merluccius*), mackerel (*Scomber scombrus*) and horse mackerel (*Trachurus trachurus*). Hake made contact with the grid bars (with 30 mm bar spacing) enabling length selection. The other two species were guided by the grid to the escape opening in the upper panel. A square mesh panel (mesh size 100 mm, length 1.8 m) placed behind the grid could improve escapement of pelagic species considerably (Fonseca et al., 2005).

Differences in contrast in the netting itself can also affect fish reactions. This led to the design of the so-called 'black tunnel', which can be interpreted as the gaping mouth of a predator. In an experiment such a black tunnel evoked strong avoidance reactions in mackerel (Glass and Wardle, 1995; Glass et al., 1995). The idea was that it can be used to improve selectivity in commercial trawls.

When heaving in a pelagic trawl fish are led toward the aft part and codend and pressed together, which may deteriorate catch quality. In Dutch midwater trawling the aft part of the net is usually not heaved in (on a stern ramp) at once, but taken in by parts using the net hauler and the lazy decky. Nowadays fish are pumped in using a large fish pump with water, and the aft part of the trawl remains in the sea.

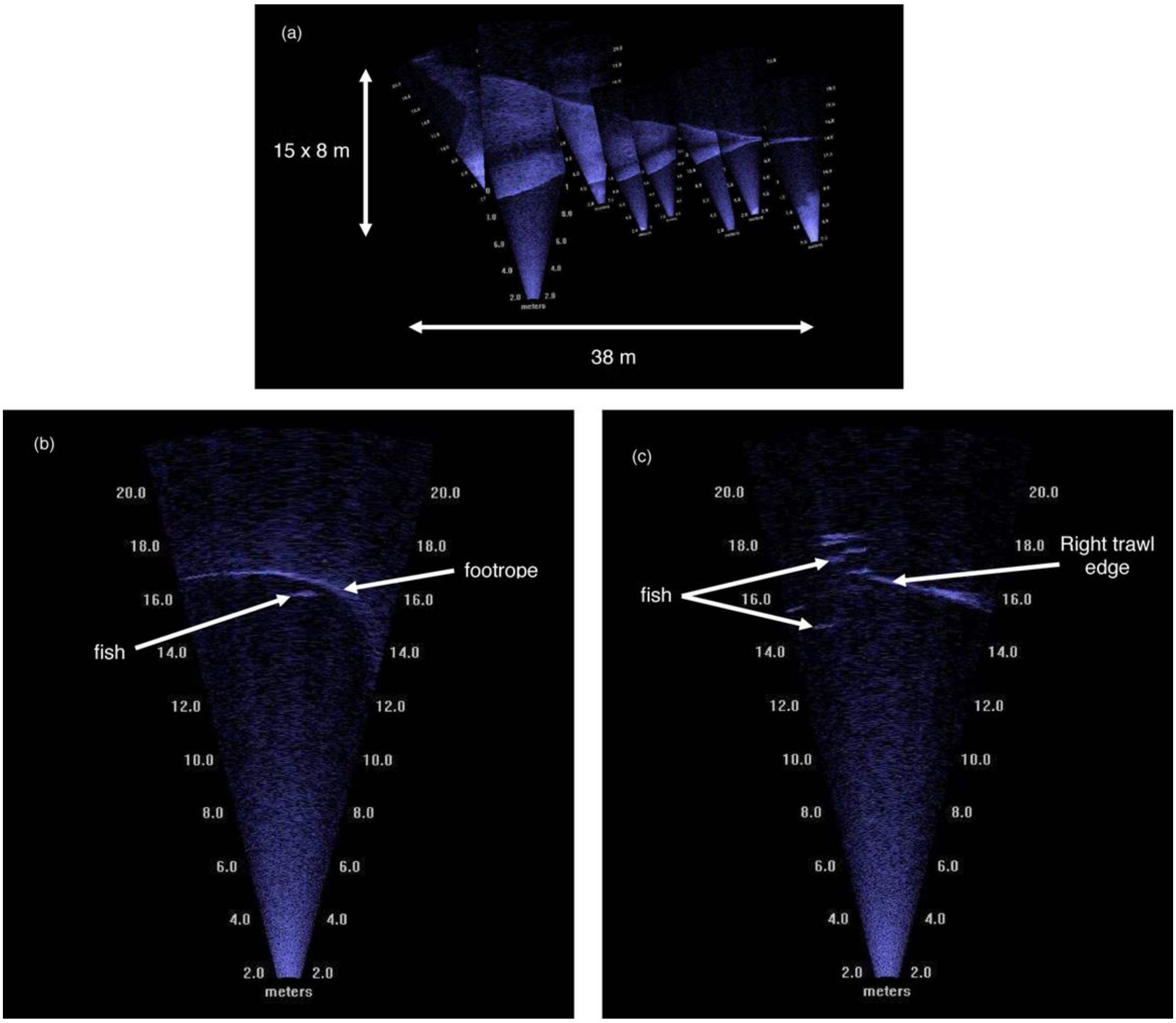


Figure 19. Form and orientation of the net (a), DIDSON recording of the ground rope with a fish at 16 m in the middle (b), DIDSON recording of the right side of the net (c).

A study using a small pelagic survey net towed at the surface using the acoustic DIDSON camera in the Czech Lake Zelivka revealed that 76% of fish were captured, and 24% escaped. A higher percentage (44%) avoided the trawl during the day than during the night (6%) (Rakowitz et al., 2012) and Figure 19. The species under study were: common bream *Abramis abramis*, roach (*Rutilus rutilus*), bleak (*Alburnus alburnus*), perch (*Perca fluviatilis*), ruff (*Gymnocephalus cernuus*) and pikeperch (*Stizostedion lucioperca*).

A recent study in Faroese waters showed that blue whiting (*Micromesistius poutassou*) and herring (*Clupea harengus*) can escape from the aft part of a trawl (Vónin 640 m pelagic survey trawl with 60 m horizontal and 40 m vertical opening and meshes of 16 m in the front part down to 40 mm in the codend), respectively at: 0.6–12% and 2–21%. Blue whiting escaped primarily from a panel with 200 mm mesh size (at 400 m depth), herring from the panels with 80, 200 en 400 mm meshes at 200 m depth. The towing speed varied between ~1.7-1.9 m s^{-1} (Skúvadal et al., 2011).

Fish survival

Many researchers conducted survival experiments on discard fish and fish escaping from codends of towed nets at sea. The chances of survival differed considerably among species. They were fairly high for cod (*Gadus morhua* L.), haddock (*Melanogrammus aeglefinus* L.) and whiting (*Merlangius merlangus* L.) escaping from codends under water (Main and Sangster, 1990; Sangster and Lehmann, 1993; Sangster and Lehmann, 1994; Sangster et al., 1996). Heaving a net to the surface reduces survival probabilities, especially for species having a swim bladder (by baro-trauma). Exposure to air on deck causes survival to drop quickly. Pelagic species showed low survival. Baltic herring of 12 cm showed 72% mortality after 7 days, and for sizes 12-17 cm this was 30%. After 14 days this increased to 91% and 62% respectively. The codend mesh size was 26 mm and 36 mm. The cause of death was presumably a combination of fatigue and scale loss. Most escapement was seen in small fish and strongest reactions at day light (Suuronen et al., 1996; Suuronen et al., 1997).

Crowding of fish inside a net affects the chances of survival. A trial with a net pen on Atlantic mackerel at densities varying from 3-500 fish m^{-3} showed a rapid increase of mortality with time and fish density, see Figure 20 and (Lockwood et al., 1983). Similar effects may arise inside trawl nets.

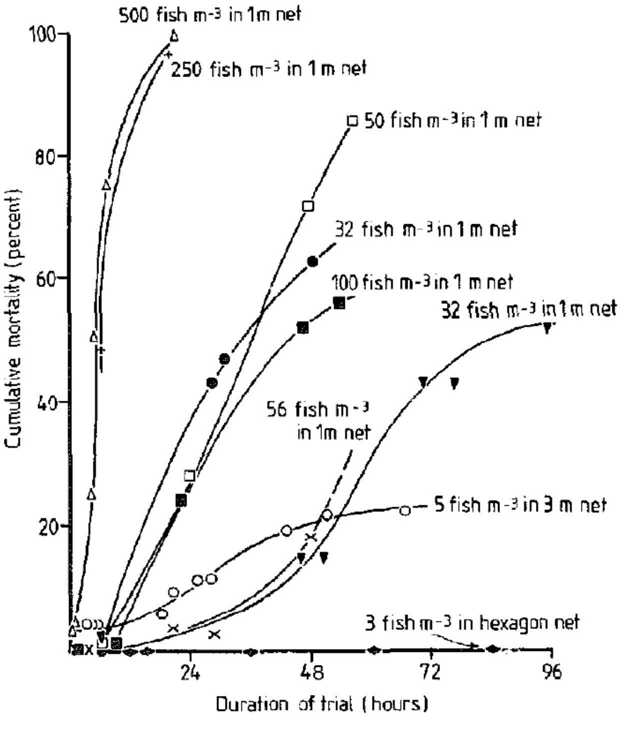


Figure 20. Cumulative mortality of Atlantic mackerel in trials in a net pen as a function of stocking density, from (Lockwood et al., 1983)