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Promoting species separation in trawl gears by using rigid grids and light systems

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Todas as correções determinadas pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

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Abstract

In the last decades, it has been recognized that many fisheries were overexploiting stocks compromising the productivity of natural ecosystems. As such, the increasing demand for fish supply due to world population growth, implies the need for an improved management of marine resources. Among the different (and complimentary) approaches it is essential to develop new ways of reducing bycatch and discards without compromising the capture of target species. Numerous studies worldwide have focused on commercial gear modifications that improve size and species selectivity, thus improving the fishing pattern of those gears.

In the present study, two different experiments were carried out demonstrating that a potential reduction in bycatch can be obtained by inserting sorting grids in trawl gears. The results obtained with the crustacean grid in the South of Portugal show the potential of separating fish (blue whiting, *Micromesistius poutassou*) from crustaceans (Norway lobster, *Nephrops norvegicus*) into an upper and a lower codend, by making use of their behavioural differences towards the grid. About 80% of the blue whiting was caught in the upper codend, whereas a similar percentage of Norway lobster was retained in the lower one. The second experiment involved a lighted grid, set into different layouts, tested in the North Sea, where several species were evaluated regarding their reaction to light. Lemon sole (*Microstomus kitt*) was the species with the most noteworthy results; in one of the gear layouts, 64% of the fish entering the trawl crossed the grid into the control codend, when the lights were on.

Keywords: sustainable fisheries; trawl fisheries; gear modifications; size- and species- selection; sorting grids; light systems.

Resumo

Nas últimas décadas, tem sido reconhecida a sobre-exploração de stocks por parte de muitas pescarias, comprometendo a produtividade dos ecossistemas naturais. Deste modo, a grande procura de pescado como fonte alimentar devido ao crescimento da população mundial implica a necessidade de uma gestão adequada dos recursos marinhos. Entre as diferentes (e complementares) abordagens, é essencial desenvolver métodos de pesca que reduzam as capturas acessórias e as rejeições sem comprometer a captura das espécies alvo. Um grande número de estudos a nível mundial tem focado as alterações às artes de pesca, visando a melhoria da seletividade intra e interespecífica, melhorando assim o padrão de pesca.

Neste estudo, dois ensaios em redes de arrasto demonstraram que uma redução potencial das capturas acessórias pode ser obtida através da adoção de dois métodos diferentes: a inserção de grelhas seletivas e a utilização de luz artificial em locais estratégicos. Os resultados obtidos com a grelha de crustáceos no sul de Portugal demonstram o potencial da grelha para separar espécies de peixe (verdinho, *Micromesistius poutassou*) de crustáceos (lagostim, *Nephrops norvegicus*) em dois compartimentos diferentes: sacos superior e inferior, explorando as diferenças comportamentais entre espécies. Cerca de 80% do verdinho foi capturado no saco superior, enquanto que uma percentagem semelhante de lagostim foi retida no saco inferior. O segundo ensaio envolveu o uso de uma grelha, iluminada por intermédio de cabo de fibra ótica, no Mar do Norte, ao largo de Aberdeen, Escócia. O objetivo foi testar a reação de diversas espécies face à grelha, com e sem iluminação, em dois layouts diferentes. A solha-limão (*Microstomus kitt*) foi a espécie com o resultado mais notável, onde, num dos casos, 64% dos indivíduos entrados na rede, atravessaram a grelha, quando esta estava iluminada, sendo retidos no saco de controlo.

Palavras-chave: pesca sustentável; pesca de arrasto; seleção intra e interespecífica; modificações no equipamento de pesca; grelhas seletivas; sistemas de iluminação.

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Abbreviations

BRD - Bycatch Reduction Device

CFP - Common Fisheries Policy

EAFM – Ecosystem Approach to Fisheries Management

EU – European Union

ICES - International Council for the Exploration of the Sea

FAO - Food and Agriculture Organization of the United Nations

MSY - Maximum Sustainable Yield

MLS - Minimum Landing Size

PET - Polyethylene

SF – Selection Factor

TAC – Total Allowable Catch

UK – United Kingdom

IUU - Unreported and Unregulated fisheries

WPUE - Weigh per Unit of Effort

Introduction

Commercial fisheries: Importance and impacts

In the last few decades, fish food supply has increased at an average annual rate of 3.3%, outpacing the world population growth at 1.6%. Global capture fishery production has reached large numbers in 2014, exceeding 93.4 million tonnes and, although captures in marine waters are stabilized around 80 million tonnes, capture in inland waters seems to be growing continuously, but not surpassing 13% of the total global capture (FAO, 2014; 2016).

With a growing world population, the need for increased food supply from fish is clear. Most populations have always been dependent on fish for feeding, remaining today an important and strategic food source. Worldwide fish consumption increased from 9,9 kg *per capita* in the 1960s to 19,7 kg in 2013 and continues to rise (see **Fig. 1**), driven mainly by a strong expansion of fish production with more efficient distribution channels and a combination of population growth, reduction in wastage, rising incomes and

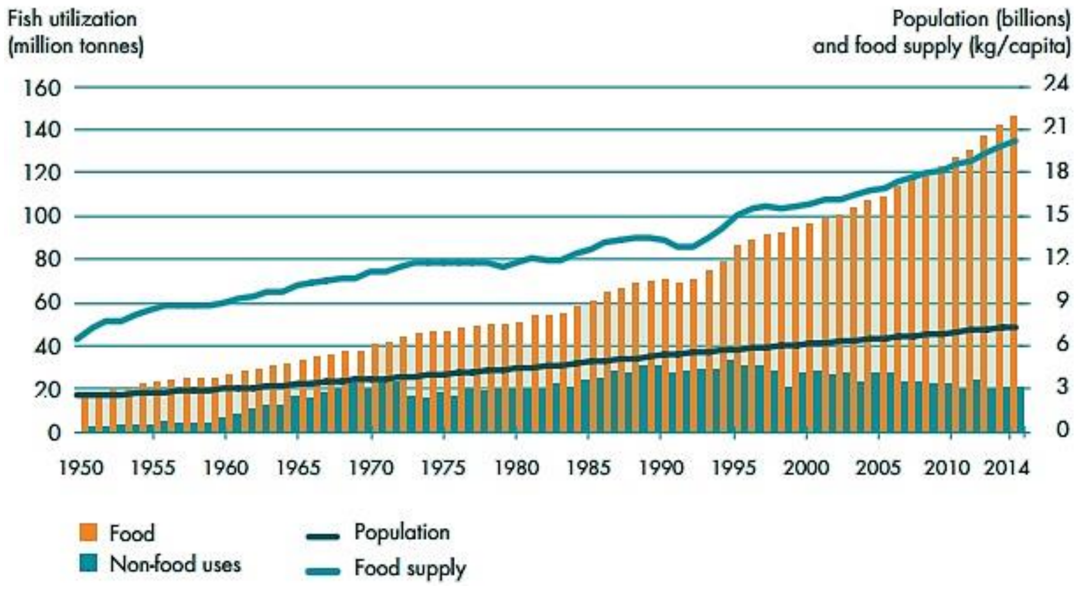

Figure 1. World fish utilization and supply (FAO,2016).

urbanization (FAO, 2016). Fishery production usually occupies a relevant position in national planning of less developed countries because of its contribution to food security and also for being part of trading agreements with developed countries (FAO, 2014). The employment created by fisheries and aquaculture provides the income of fishers' families that goes up to millions of people worldwide. Aquaculture has been showing an increasing trend for the last years and accounted for 44.1% of total production in 2014, with 35 countries producing more farmed than wild-caught fish (FAO, 2016). Recent data shows that there are more than 37 million fishers in the world, an increasing number since 1990, and fishery production also links a variety of activities such as fish processing, ice production, naval industry, fishing gear manufacturing, packaging, marketing and distribution, which offers millions of job opportunities (Ye *et al.*, 2013; FAO, 2014).

Fisheries are thus driven by social and economic demands, however, they are dependent on and limited by the productivity of natural ecosystems. There is a massive pressure on fishery resources thereby reducing stock abundance and biodiversity, leading to stock's overexploitation, economic loss and reducing food availability (Ye *et al.*, 2013).

Since the 1950s, fishing effort has expanded from the coastal waters of the North Atlantic and West Pacific to the open-ocean, southern hemisphere, and tropics. After the First and Second World Wars there was an improvement of commercial vessels, which were equipped with diesel engines, sophisticated equipment for eco-location and refrigeration that enabled longer and more effective fishing trips (Swartz *et al.*, 2010). At a rate of almost a degree of latitude per year, expansion was greatest from 1980 to the early 1990s and the difficulty to access the poles turned these areas into the final frontiers in this expansion (McClanahan *et al.*, 2015).

Pollution and coastal development often cause depletion of fish stocks around the world (Ye *et al.*, 2013). Microplastics, oil spilling and fertilizers runoff are some of the sea pollutants resulting from human activities that affect biomes vulnerability. Coastal areas in particular, are densely populated due to several key activities such as maritime transport, tourism, and fishing, yet they are also home to species and habitats often threatened by population settlement (United Nations, 2015). The decline in fish biomass, both target and incidental catch, is a fundamental issue of fisheries exploitation, but reducing the anthropogenic effects on ecosystems and biodiversity is an increasing concern for modern fisheries management.

According to FAO's analysis, the fraction of assessed stocks fished within biologically sustainable levels has exhibited a downward trend, declining from 90% in 1974 to 69% in 2013. In this year, the global production in marine fisheries was 80.9 million tonnes, with the Northwest Pacific Fishing Area having the highest production of 21.4 million tonnes - 27% of the global marine catch (FAO,2016). Regarding the same report, in 2011, 29% of fish stocks were estimated as fished at a biologically unsustainable level (overfished), increasing to 31% in 2013. Of the total number of stocks assessed in 2013, fully fished stocks accounted for 58.1% and underfished stocks 10.5%, meaning the underfished stocks have been decreasing almost continuously, but the fully fished stocks increased (**Fig.2**); congruently, the percentage of stocks fished at biologically unsustainable levels increased, especially in the late 1970s and 1980s, and then more slowly in the last few years reaching 31% in 2013 (FAO, 2014; 2016). By definition, stocks fished at biologically unsustainable levels have an abundance lower than the level that can produce the Maximum Sustainable Yield (MSY) and are therefore being overfished (FAO, 2014). Keeping biomass at 25–50% of unexploited levels typically maximizes the yields while going below this level may result in overfishing (McClanahan *et al.*, 2015).

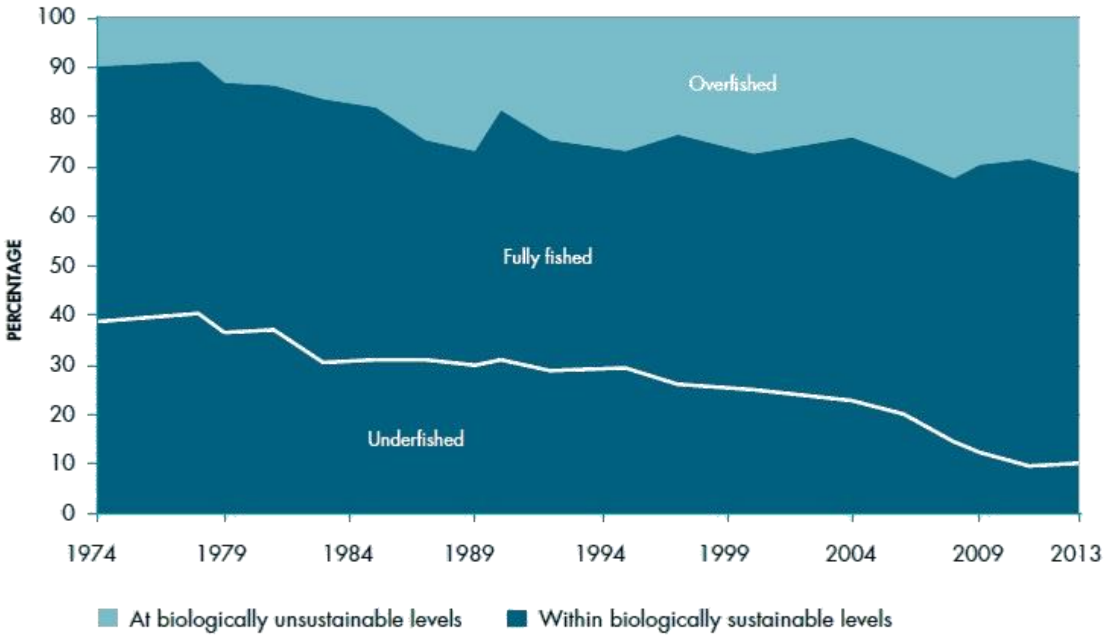

Figure 2. Global trends in the State of World Marine Fish since 1974 (FAO,2016). Note: The light line divides the stocks within biologically sustainable levels into two subcategories: fully fished (above the line) and underfished (below the line).

Unintended capture of fish, crustaceans, marine mammals, sea turtles and seabirds by fishing gear, take place in virtually all fisheries. Bycatch is the total catch of non-target animals whereas the fraction thrown overboard forms the discards (FAO, 2016). Many fisheries worldwide are characterised by high discard rates, being a significant problem as it has a substantial impact on ecosystems. Discards are the portion of animal and plant material in the catch, of both commercial and non-commercial value, that is returned to the sea (Feekings *et al.*, 2012; Sardà *et al.*, 2013) dead or dying. They have long been regarded as one of the key issues in commercial fishing by representing production and yield foregone, resulting in waste of resources and consequently future economic loss in fisheries, as well as population and ecosystem level impacts (Veiga *et al.*, 2016). Discards occur due to many reasons, including when fish are caught under the minimum landing size, have low or no commercial value (Machias *et al.*, 2001), catch is damaged or the species quota is reached (Feekings *et al.*, 2012). Even the target species are often discarded due to regulatory constraints or economic reasons (FAO, 2005). Trawl fisheries have been identified as the primary sources of overfishing and bycatch worldwide leading to high mortality in non-target species and alter ecosystem structure and function (Peckham *et al.*, 2015). But other gears, including gillnets and longlines, can also contribute to bycatch and discards of elasmobranchs, mammals and seabirds, with high mortalities (Uhlmann and Broadhurst, 2015).

Fish supply is affected by the problems described above, with direct consequences to the population's sustenance and, in worst cases, survival. As the global population continues to rise, the priorities of fisheries management include food security and the market supply of fish products (European Parliament and Council, 2013) with the main goal being contributing to an adequate nutrition worldwide.

Management measures and improvement of fishing gears' selectivity

To respond to these fishery pressures, policies are applied to reduce the impacts of fisheries worldwide. The Common Fisheries Policy (CFP) was implemented in the European Union in the 1970s aiming a sustainable way of fishing, by applying a set of rules for managing fishing fleets. The Food and Agriculture Organization (FAO) provides fisheries data since the 1950s and promotes sustainable management and utilization of natural resources. An example of a fishery regulatory measure is the Total Allowable Catch (TAC). TACs are estimated for each fish stock, most frequently every year, with the fishery being closed when the year's cumulative catch has reached the TAC. The stock level should be above its biological and economic equilibrium if the TAC is correctly quantified and imposed (Beddington *et al.*, 2007), which over the years has not been possible to implement in many commercial species (EU, 2013).

Several measures are implemented to reduce incidental catch of non-target species and discards, such as prohibiting or limiting the use of certain gear types in defined areas or seasons, defining zones reserved for traditional fishing activities and technical measures that consist of changes in the design or rigging of fishing gear (FAO, 2016). The new landing obligation requires all catches of regulated commercial species on-board to be landed and counted against quota. In the European Union (EU) this measure serves as a driver for more selectivity, compelling fishermen to adapt and use more sustainable methods in fisheries. The CFP aims to implement the Landing Obligation and it will be gradually introduced across stocks so that by 2019 all quota species are included in this measure (European Commission, 2013).

According to FAO Fishery manager's guidebook (2002), the ideal fishing gear should be: 1) highly selective for the target species and sizes, with negligible direct or indirect impact on non- target species, sizes and habitats; 2) effective, giving high catches of target species at lowest possible cost; 3) quality orientated, producing catches of high quality. Unfortunately, no fishing gear fulfils the complete list of desired criteria and properties. However, in recent years there has been a growing focus on providing biologically and economically sustainable exploitation of fish stocks leading to work aimed at improving both the size and species selectivity of towed fishing gears (Krag *et al.*, 2015).

Increasing research has been carried out on gear modification to sort out unwanted species and improve size-selection. Trawl fishing, especially bottom trawl, is a very poor selective method, which means a large number of individuals from the target species are caught under their minimum landing size as well as commercial and non-commercial bycatch species, contributing to the large quantities of fish and invertebrates discarded at sea (Ordines *et al.*, 2006). To reduce the impact of trawling on the ecosystems, studies have taken place all over the world.

Bycatch poses threats especially to vulnerable large aquatic predators in consequence of their slow reproductive rates (Oksanen *et al.*, 2015). The 'Simple Anterior Fish Excluder' (SAFE), tested by McHugh *et al* (2015) on beam trawls was used with good results, significantly reducing total bycatch up to 58%, depending on the species, maintaining targeted prawn catch. Further work is required to refine the tested SAFEs; however this concept might represent an effective approach for improving the selectivity of shrimp trawls. For seabird bycatch, numerous gear-based mitigation measures have been proposed. Melvin *et al* (2014) tested combinations of two primary mitigation measures in a pelagic longline fishery - the use of weight and bird scaring devices. They confirmed that, regardless of time of day, weighted branch lines with two bird-scaring lines reduced bird attacks by a factor of four and secondary attack rates and seabird mortality rates by a factor of seven compared to unweighted branch lines.

In trawl fisheries, the topless trawl design was developed to improve species selectivity. In this type of trawl, the headline is cut back when compared to the footrope, to allow fish to escape upwards and over the net. Krag *et al* (2015) found a significant topless effect for haddock and Atlantic cod and no effect for lobsters. These results are related to different species' behaviour and demonstrate an example of a method used to improve catch selectivity and thus sustainability in the fishery. Eayrs *et al* (2016) also tested a topless trawl on a commercial trawler with a much greater headrope to footrope ratio, comparing to other studies in the New England region. Cod catches were reduced by 51% compared to the traditional bottom trawl and there was no reduction in the catch of other species.

The use of square mesh codends in trawls has also been investigated in the last decades to improve selectivity, showing a significantly higher mean selection length (L_{50}) when compared to the diamond mesh codend (Campos *et al.*, 2003; Bahamon *et al.*, 2006; Lucchetti, 2008; Sala *et al.*, 2008) and narrower selection ranges in square mesh codends comparing to diamond mesh codends (Robertson and Stewart, 1988; He, 2007). The use of combined meshes or panels has similarly been reported with good results. To reduce Atlantic cod bycatch, Madsen et al (2012) tested a four-panel section with an escape window to improve the escape of this species. The results showed a substantial escaping proportion reaching nearly 64% for cod and higher percentages for other species.

In relation to the use of rigid grids, they have long been tested in several studies and successfully used to reduce the bycatch of juvenile fish in shrimp trawl fisheries throughout the world (Broadhurst and Kenelly, 1997; Polet, 2002; Eayrs, 2007). In the late 1980's, the Nordmøre grid was developed in Norway to reduce bycatch of juvenile fish and a few years later its use became mandatory in the Norwegian shrimp trawl fishery. Fish are guided by the grid towards the escape opening in the top of the codend while shrimps and other small animals pass through the grid and enter the codend. The design of the grid has been constantly changed and improved throughout the years. For instance, the grid inclination has demonstrated to affect the percentage of shrimp loss and the escape of unwanted species (Grimaldo, 2006); lower grid angles tend to increase the escape of fish but also the percentage of shrimp loss. Grimaldo (2006) also reported that when the towing speed is reduced, there's an increase on the escaping of unwanted species.

In the last decade, several methods were tested in Portuguese trawl fisheries, with the aim of increasing selectivity of the crustacean fishery for species such as Norway lobster (*Nephrops norvegicus)* and reducing bycatch and discards. Several fish species are caught along with crustaceans and later discarded (Borges *et al.*, 2001), such as blue whiting (*Micromesistius poutassou*), which usually makes up most of the catch and has low commercial value. In South Portugal, crustacean bottom-trawlers discard large amounts of low-value or non-commercial species, averaging 70% of the total catch with fish making up most of the discards by weight (Castro *et al.*, 2005). Campos *et al* (2003) tested a codend mesh size increase from 55 to 60 and 70mm and a change of mesh configuration from 55mm diamond to 55mm square mesh, in the Portuguese south coast. These alterations proved to significantly reduce the amount of bycatch that is subsequently discarded particularly for blue whiting, also enhancing minimum landing sizes (MLS[1]) of crustaceans. In what concerns to the use of grids for selectivity improvement, this issue has been previously addressed in the same geographical area, by testing the efficiency of a modified Nordmøre grid that excluded some of the most captured non-commercial bycatch species. In this study, Fonseca *et al* (2005) results were very promising; high bycatch species exclusion, yet, there was a significant loss of rose shrimp and Norway lobster through the escape zone.

Fish reaction to light has also demonstrated to affect fish selectivity. Experiments in the North Sea go back to 1989 where Glass and Wardle tested trawl catch under light and dark conditions. They report that fish, in the absence of vision, are unable to react to an approaching fishing net being captured, unlike in high light levels where fish avoid the net, with only one fish captured during all trials. As a consequence of these behaviour patterns, catch rates of different species vary between day and night and this has long been recognized by fishermen which direct their efforts accordingly. Light levels influence the catchability, and once in the path of a towed fishing gear, behaviour towards it is thought to be largely governed by visual stimuli (Jones *et al.*, 2004). Therefore, changes in light levels would be expected to affect the ability of fish to see these stimuli and react to them. It has been proven in the past that fish can be affected by artificial light stimuli and even acquire conditioned reflexes to an external stimuli (Pyanov, 1993; Ryer and

[1] With the implementation of 'Landing Obligation', Minimum Landing Sizes were renamed as 'Minimum Conservation Reference Sizes' (MCRS). For simplicity, we will keep the old designation throughout this thesis.

Olla, 2000; Ozbilgin *et al.*, 2004; Marchesan *et al.*, 2005). These behavioural reactions play an important role in what happens during the capture process and recent research on this subject has been made to improve fisheries selectivity. Behavioural effects of artificial light of different frequencies and wavelengths were investigated on four species by Marchesan *et al* (2005): European seabass (*Dicentrarchus labrax*), the common grey mullet (*Mugil cephalus)*, the gilthead seabream (*Sparus auratus*) and the striped bream (*Lithognathus mormyrus*). The results demonstrated the common grey mullet and the gilthead seabream had the strongest attraction to light and, as for the other species, some showed less interest or even repulsion induced by colours or light intensity. In an attempt of testing the cod attraction to green light in floating plots in the Baltic Sea, Bryhn *et al* (2014) demonstrated that fish are affected by visual stimuli with increased catch (up to 80% increase in WPUE – Weight per Unit of Effort) of large (>38 cm) cod when the pots with a green lamp were used,. Hannah *et al* (2015) investigated how the addition of artificial light in the rigid-grid bycatch reduction device (BRD) and along the fishing line of an ocean shrimp trawl altered fish bycatch and ocean shrimp catch. Their results represent the first successful application of artificial light to modify fish escapement behaviour in a trawl to greatly reduce bycatch, as it appears to have significantly increased the passage of fishes through restricted areas. These findings show there is a notable difference in fish species' behaviour in relation to light stimuli that can be used in fisheries to attract or repel fish. Summerbell and O'Neill (2015) investigated in this area, testing a prawn trawl with a horizontal separator panel. Fibre optic light cables were attached to the fishing line and to the leading edge of the horizontal separator panel. Several species were caught such as haddock, whiting and cod. Fish that went above the panel were caught in the upper codend while those going below the panel were caught in the lower codend. The results showed that the light cables only seemed to affect fish behaviour during night, although it is not clear whether the fish are reacting directly to the light cable or to something associated with the additional illumination provided by the light cable.

There are several bycatch reduction methods used in fishing gears. Even though all of them have the same goal, it is not always possible to guarantee fish survival after they are selected out of the gear. In this line of thinking, it is essential to use, whenever possible, methods that provide the least physical contact with the gear itself. The use of different mesh sizes and shapes may improve selection but it can cause injury and even death to the individuals that escape. Therefore, the use of grids will sort out the individuals before inducing contact with the mesh, In this work, two different gear modifications were investigated with the aim of reducing bycatch in trawl fisheries, by means of new fishing technologies. On one hand, the grid experiment carried out in Portuguese waters aimed at solving the problem of loss of target species, identified by Fonseca *et al* (2005). On the other, the experiments in Scottish waters aimed at highlighting the potential of using light to enhance the visibility of a grid, and hence its selectivity, for several commercial North Sea species.

Materials and methods

Crustacean grid selectivity trial

Data regarding a trial were analysed at the Portuguese Institute for the Ocean and Atmosphere (IPMA). A rigid grid was tested in a crustacean-trawl, making use of the expected behavioural differences between fish and crustaceans to promote their separation within the gear and possible exclusion of non-targeted species. The Norway lobster is known to have a passive behaviour, being its selection mainly mechanical. On the other hand, the blue whiting is a species that avoids the grid and tends to escape though the grid openings. This system offers the possibility to use different mesh sizes, on both codends, aiming the improvement of the exploitation pattern of these species groups - important when using this type of gear in a multi-specific fishery, as in meridional Atlantic areas.

Grid design

The grid dimensions were 1.5 m x 1.0 m and the spacing between bars was 20 mm. The grid was provided with an inferior opening of 20 cm high designed for the direct passage of Norway lobster (**Fig.3**.). An upper opening, without bars and with 40 cm high was designed to allow passage to the catch fraction retained by the grid leading to the cover. The extension piece inserted in the trawl (where the grid was placed) was made of polyethylene (PET) mesh size of 50mm, with a total length of 3 m.

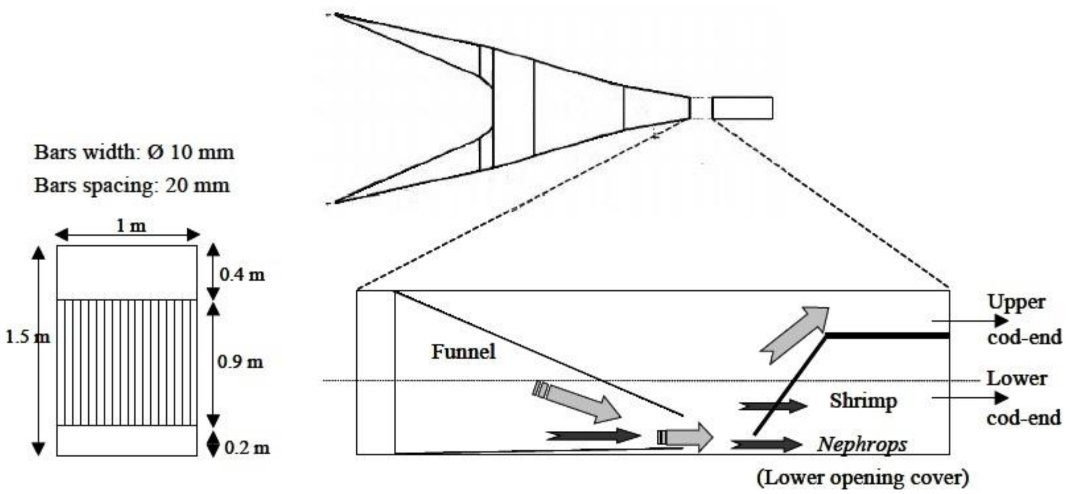

Figure 3. Technical drawings with grid details. Selective grid system designed for the separation between crustaceans and fish in two different compartments. The main flow of fish and crustaceans is narrowed by the funnel which directs the catch into the inner codend – depending on their movement, the species are then caught in one of the three codends.

The grid directed the catch to three distinct codends (**Fig.4**). The lowermost codend (inner codend) retains the catch fraction passing through the lower grid opening. The fraction passing through the grid bars are caught in the lower codend (between the upper codend and the inner codend) and finally the fraction passing through the upper bar opening is captured in the upper codend. All codends were entirely made of polyamide (nominal) mesh size of 20 to 30 mm (1.0/1.2 twisted and 2.0/2.5 braided mm thickness, respectively).

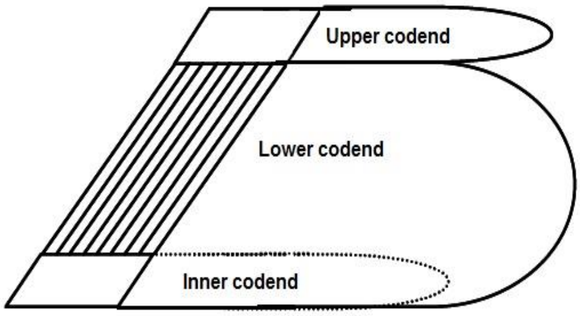

Figure 4. Gear compartments. The upper bar-less opening leads to the upper codend and the lower opening leads to the inner codend. The bar zone leads to the lower codend (Not to scale).

Data collection

A total of 18 one-hour valid hauls were conducted on board IPMA R/V “Noruega”, a 47.5 metres overall length 1500 HP stern trawler. The experiments were carried out from 23rd to 27th July 2007, in Norway lobster fishing grounds off the Portuguese south coast (**Fig.5**) between Tavira (36.7◦N, 7.5◦W) and Faro (36.9◦N, 7.9◦W), at depths between 420 and 620 m. After each haul, catches in the codends were counted and weighed separately. Carapace length (mm) of Norway lobster and total length (cm) of commercial fish species such as blue whiting, as well as conger (*Conger conger*), hake (*Merluccius merluccius*) and blackbelly rosefish (*Helicolenus dactylopterus*) were measured.

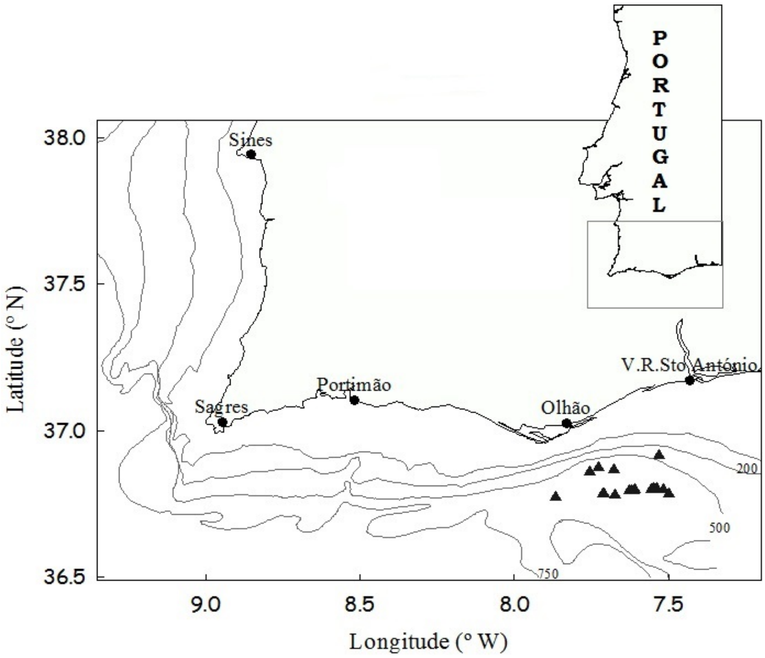

Figure 5. Location of the experimental hauls (black triangles) carried on the R/V "Noruega" crustacean trawl where a rigid grid was tested.

Size-selection analysis

The main purpose of this work is to evaluate the separation of fish from crustaceans into separated (upper and lower) codends. Nevertheless, any grid induces a potential size-selection for those species/individuals physically contacting it. The selection by size is directly related to the grid bar spacing, which in turn will condition the effective separation between codends. As such, whenever possible, size-selectivity (logistic) curves were estimated for the main species, excluding the fraction that entered directly through the lower opening, using the following parameterisation (1):

$$r(l) = \frac{\left(\frac{q1}{q2}\right)*e^{\left(2*\log(3)*\frac{(l-L50)}{SR}\right)}}{\left[1+\left(\frac{q1}{q2}\right)*e^{\left(2*\log(3)*\frac{(l-L50)}{SR}\right)}\right]} \qquad (1)$$

where r(l) is the probability that a length l fish is sorted by the grid, q_1 and q_2 are the subsampling fraction of upper and lower codend, respectively (Millar *et al.*, 2004). L_{50}, length at which the probability of being retained is 50% and selection range (SR: L_{75}–L_{25}).

The length frequency data from each haul were appended into single files. These files also contained the relevant covariates (i.e., explanatory variables described below), including the sampling fraction for all hauls where the catch was sub-sampled. Modelling of selectivity data was carried out using the non-linear mixed-effects approach of Millar et al. (2004), implemented with the SAS® NLMIXED procedure. This approach allows for the simultaneous inclusion of the effects of different (quantitative and qualitative) covariates and account for between-haul variability, in a context where selectivity cannot be estimated on a haul-by-haul basis. Moreover, in the process of fitting the selection curves, the model explicitly includes the effect of sub-sampling, thereby avoiding the need to raise the sampled length frequency data (Millar, 1994).

The main covariates of interest were: total catch weight per haul, species catch weight and depth. These variables had previously been identified as a source of uncontrolled between-haul variability in selectivity in several studies (O'Neill and Kynoch, 1996; Campos *et al.*, 2002; 2003). Between-haul variability was included by allowing length at 50% retention (L50) and Selection Range (SR: L75 – L25) to vary randomly according to a normal distribution (Millar *et al.*, 2004). Specifically, the L50 value for the replicate haul in each experiment was modelled as (2):

$$\mathrm{L}_{50} = \alpha + \delta wt_r + \gamma ws_r + \lambda d_r + \varepsilon_r \qquad (2)$$

Where *wt* denotes the total catch weight, *ws*, the total species weight, and *d* denotes depth. The ε are independent and identically distributed Normal (0,σ2) and represent the random between-haul variation. The significant variables were retained as the result of a backward stepwise selection. Lack of convergence while running the model with both random L_{50} and SR led us to consider a fixed selection range:

$$\mathrm{SR} = \mu^{SR}$$

ANOVA and a two-sample t-test assuming equal variances with a confidence level of 95% was used to determine if there were significant differences in mean size for blue whiting and Norway lobster among the different codends.

Fish selectivity using artificial light

Fishing trials took place on the Marine Research Vessel (MRV) Alba na Mara, in Aberdeen, Scotland. Two different layouts were tested, based on existing behavioural differences between species and their contrasting tendency to go to the upper or lower codend. Fibre optic light cables were attached to a grid, also testing fish reaction towards light. The grid was tested with the lights on and off. The target species were haddock (*Melanogrammus aeglefinus)*, whiting (*Merlangius merlangus*), Atlantic cod (*Gadus morhua*), lemon sole (*Microstomus kitt*) and other flatfish.

Gear design

The grid dimensions were 1.2 m x 0.7 m with 14.5 cm of spacing between bars (**Fig. 6**). It is essential to clarify that, in both layouts, the grids were not designed to improve selectivity by itself, as the large bar spacing does not affect selectivity, but to be able to support the light cables.

Fibre optic light cables were attached to the grid and were illuminated by a Photosynergy Ltd green LED which was powered by a 12V DC supply.

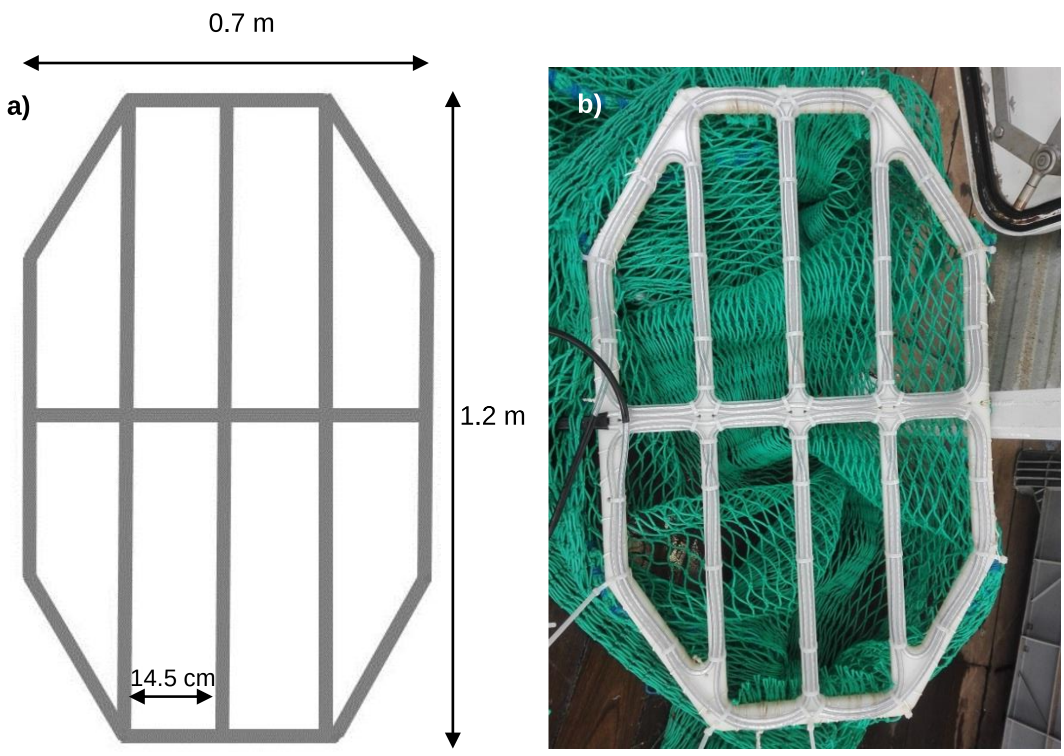

Figure 6. a) Technical drawings of the grid; b) grid photography with the light cables attached.

Two different gear layouts were tested during the trials. In the first layout, an inclined netting panel was installed forcing fish to swim to the upper codend. Therefore, the grid is below the main flow of fish, as shown in **Fig.7.a)**. This is called the Below-type design, where the upper codend is named the Main codend and the lower codend is the Control codend. In the second layout, represented in **Fig.7.b)**, the netting panel is declined,

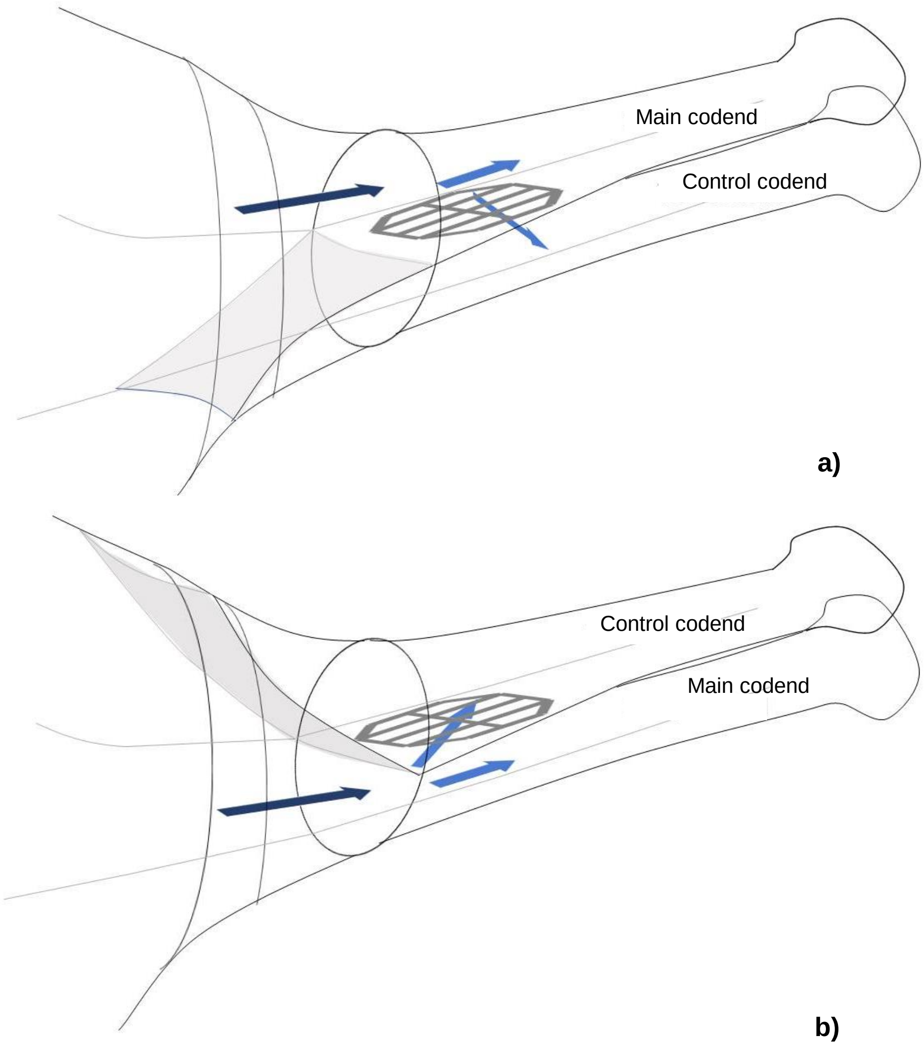

Figure 7. Gear-layouts used during trials: a) Below; b) Above.

hence the grid is above the main flow of fish. In this layout, the Main codend corresponds to the lower codend and the Control codend to the upper codend. In addition to these specifications, the layouts were tested with the lights on the grid turned on and turned off. Summing up, there are four groups of layouts tested:

- Below-on (Gear-layout: Below; Lights: On);
- Below-off (Gear- layout: Below; Lights: Off);
- Above-on (Gear- layout: Above; Lights: On);
- Above-off (Gear- layout: Above; Lights: Off).

Data collection

Experiments were carried on the MRV Alba na Mara, a 27 m overall length stern trawler owned by Marine Scotland Science – The Scottish Government. The set of trials took place from 8th until 22nd March 2017 during daylight hours and a total of 52 hauls were performed. Fishing trials were conducted in fishing grounds of the East coast of Scotland, around 10 Nm from Aberdeen (57.1◦N; 1.5◦W) and at depths ranging from 79 to 104 meters. The location of hauls is represented in **Fig.8**.

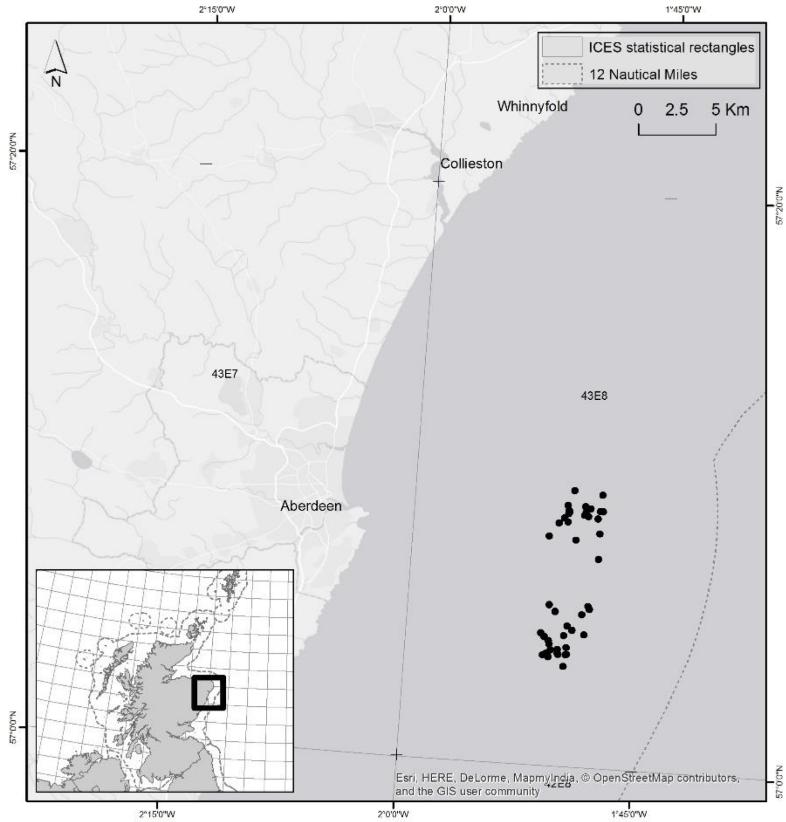

Figure 8. Location of the experimental hauls (black dots), a few miles off Aberdeen, Scotland, carried on the MRV "Alba na Mara" trawl while testing a light grid.

The first 6 hauls were aimed at testing the grid alone and collecting video footage while the trial itself took place in the subsequent 46 hauls, with a duration of 1.5 hour each.

Catches from both upper and lower codends were sorted by species and weighted. The total length (cm) of all individuals was measured, except for edible crab (*Cancer pagurus*), lobster (*Homarus gammarus*) and scallops (*Pecten maximus*). Sub-sampling took place only when the species catch was too high, which was the case for haddock in almost all hauls.

Statistical analysis

The effects of the light were evaluated on seven fish species, three of which were roundfish and four were flatfish. A preliminary analysis included plotting the catch data for each species, both in weight and number of individuals. The length frequency distributions were also analysed, as well as the proportion of fish that went into each codend. 95% confidence intervals were estimated by carrying out 1000 bootstrap repetitions and calculating the Efron 95% confidence limit, where on each repetition the haul data were selected with replacement.

A length based assessment was also carried out for each of the main species. The catches retained in the control and main codends were analysed using the smoother based methodology of Fryer et al. (2003). This analysis is in three stages:

- A smoother was used to model the log catch rate of the control codend relative to the main codend for each haul;
- The fitted smoothers were combined over hauls to estimate the mean log relative catch rate;
- Bootstrap tests were used to assess 95% confidence intervals around the mean log relative catch rate.

The analysis was on the logistic scale, and the results are back-transformed for presentation. This analysis was performed using the R software. In this analysis, the Akaike's information criterion (AIC) (Akaike, 1973) was used to compare the fits obtained and then applied in the data smoothing.

Results

Crustacean grid selectivity trial

Results are based upon the comparison of catch data obtained from 17 hauls. One haul was excluded from the data analysis given the extremely large catch of a single species, blue whiting, which, if included, would have biased the analysis.

Catch Data

A total of 556.2 kg of fish and crustacean were captured during the trial, with blue whiting being the species that made up most of the hauls by weight (62.9%; 349.8 kg. See **Fig.9**.), followed by Norway lobster with 24.8% of total catch (137.9 kg). Several other species, such as conger, blackbelly rosefish, hake and ray, were captured as well. Together, these species accounted for 12.3% (68.4 kg) of total catch. All species caught and their respective weight are presented in **Appendix 1**.

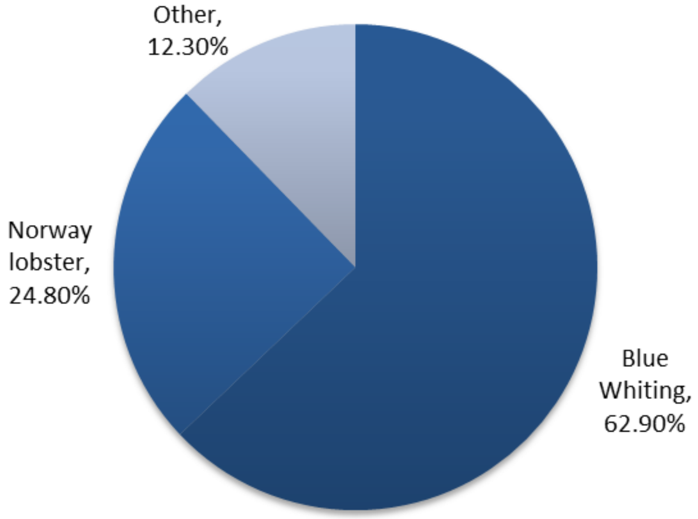

Figure 9. Catches proportion in weight of the captured species, considering all valid hauls (17 hauls).

The pooled length frequency distributions for Norway lobster and blue whiting are shown in **Fig.10**. Blue whiting ranged in length from 18 to 36 cm, with most of the fish concentrated between 25 and 33 cm. The catch was divided between the upper and inner codends, as in the lower codend the catch was practically null. Individuals around 28 cm long showed the highest catch.

For Norway lobster, the carapace length (CL) ranged between 17 and 57 mm, with just a few individuals caught below 20 mm (MLS). Catches were higher in the inner and lower codend, with only about 20% of the catch being retained in the upper codend. The highest mode was about CL= 30mm.

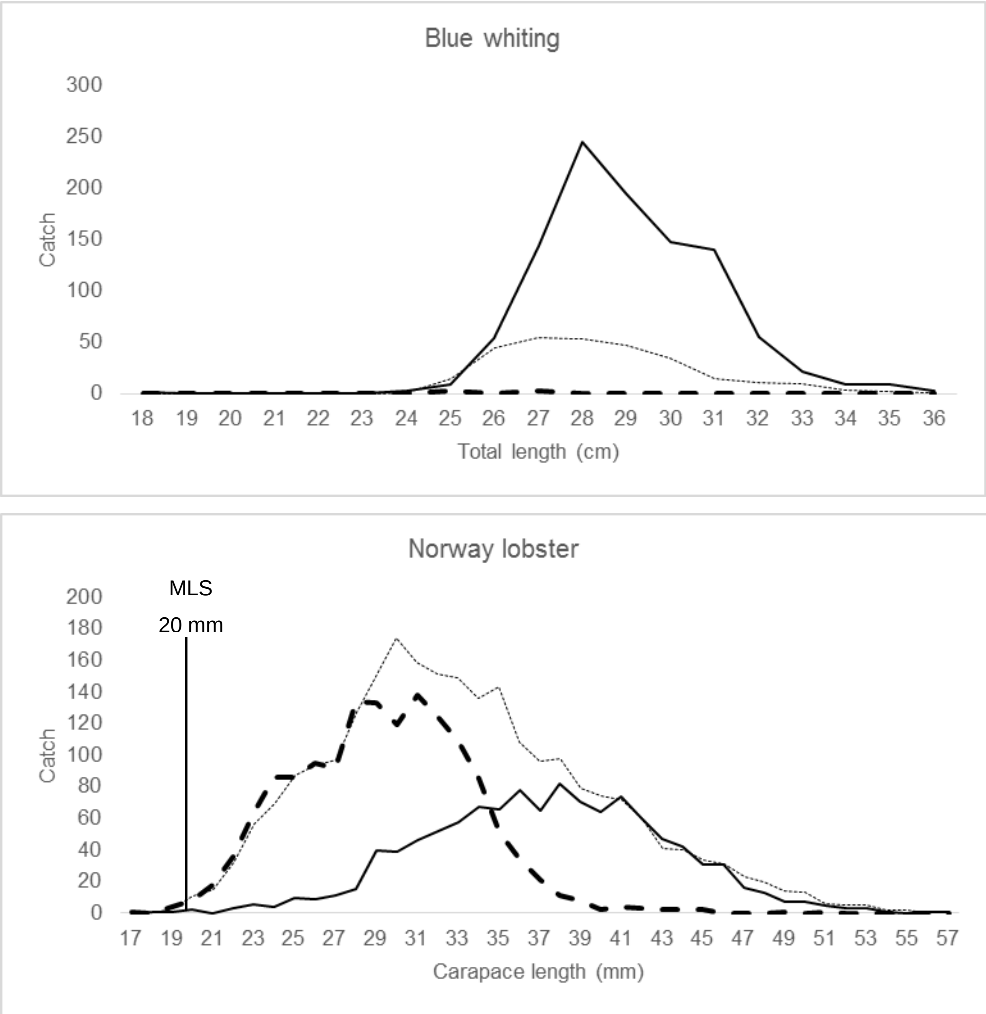

Figure 10. Length frequency distributions for blue whiting and Norway lobster. Continuous line: upper codend; dotted line: inner codend; dashed line: lower codend.

The results of the *t*-tests performed to compare the length distributions and mean size of the Norway lobster and blue whiting catches among the different compartments of the gear are shown in **Table 1**. When analysing differences of Norway lobster mean carapace length among codends, ANOVA and *t*-test revealed they were all statistically significant. The same result was observed between the upper and inner codends for blue whiting, although herein the statistically significant difference corresponded to mean sizes only 0.7 cm apart.

Table 1. Results from the ANOVA (for Norway lobster) and Student's t (t) tests (for blue whiting), comparing the length frequency distributions and mean size between the different compartments (codend, inner codend and cover). For blue whiting, only the comparison between cover and inner codend was considered because there were almost null catches in the lower codend.

	Norway lobster		**Blue whiting**	
	Average values (mm)	P value	Average values (cm)	P value
Upper vs. lower codend	37.3; 29.3	<0.001	-	-
Upper vs. inner codend	37.3; 33.3	<0.001	28.3; 29.0	<0.001
Lower vs. inner codend	29.3; 33.3	<0.001	-	-

Species sorting

Norway lobster was caught mostly in the inner and lower codends (48.5% and 29.2%, respectively), while for blue whiting an inverse distribution was evidenced. These results are linked to the behavioural differences between both species, with the blue whiting displaying an active avoidance towards the grid (**Fig.11,** left). Therefore, most of the fish was caught in the upper codend, representing 77.9% of the total catch, while catches of blue whiting in the lower codend (those who crossed the grid bars) are almost null. The remaining fishes were collected entered by the lower opening of the grid being retained in the inner codend.

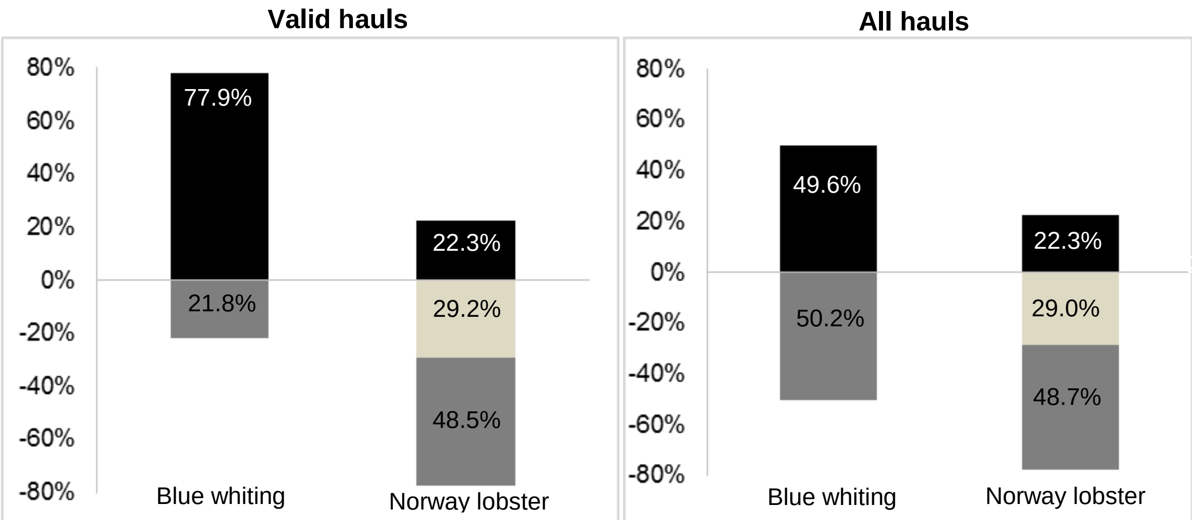

Figure 11. Percentages (in number) of blue whiting and Norway lobster, including all valid hauls and one excluded haul (right) and including only valid hauls (left). Black: upper codend; dark grey: inner codend; light grey: lower codend.

When analysing pooled data with the previously excluded haul in (**Fig. 11,** right), we observed the blue-whiting catch was divided almost equally between the upper and the inner codends. There is no alteration to the Norway lobster catch distribution, since the excluded haul was constituted almost exclusively by fish.

Size selection analysis

The results of the SAS modelling test are shown in **Table 2**, concerning the total species weight per haul. This was the covariate that demonstrated a significant influence on the L_{50} variability. For the Norway lobster, the length of 50% retention (L_{50}) is 29.7 mm and the selection-range (SR) is 6.6 mm.

Table 2. Results of the size-selectivity SAS modelling test, regarding the total species weight per haul for Norway lobster.

Parameter	Estimate	Standard Error	DF	t Value	Pr > |t|	95% Confidence Limits	
Mean L50	29.7497	0.3034	17	98.07	<.0001	29.1097	30.3897
Mean SR	6.5961	0.2736	17	24.11	<.0001	6.0189	7.1732
L50HaulSpeciesWgtPar	4.7497	0.3034	17	15.66	<.0001	4.1097	5.3897
VarL50	5.6448	2.4670	17	2.29	0.0352	0.4400	10.8497

The respective selection curve obtained for Norway lobster is presented in **Fig.12.** The model estimates obtained were α= -10.69 and β= 0.33.

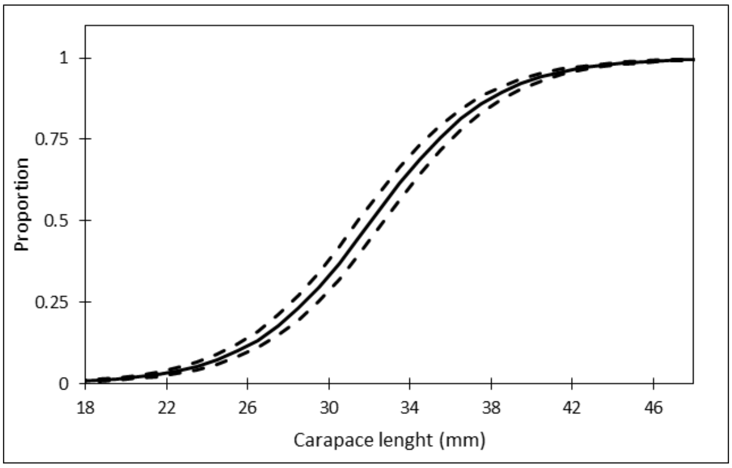

Figure 12. Length (carapace) dependent catch distribution of Norway lobster (*Nephrops norvegicus*). Dashed lines indicate the 95% confidence bands.

Fish selectivity using light

Catch Data

The most captured species during trials were haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), Atlantic cod (*Gadus morhua*), lemon sole (*Microstomus kitt*), plaice (*Pleuronectes platessa*), long rough dab (*Hippoglossoides platessoides*) and common dab (*Limanda limanda*). Other species such as herring (*Clupea harengus*), scallops (*Pecten maximus*), European squid (*Loligo vulgaris)* and monkfish (*Lophius piscatorius*) were also caught, however in smaller quantities.

The percentage composition of total catches, in weight and by species, is shown in **Fig.13**.

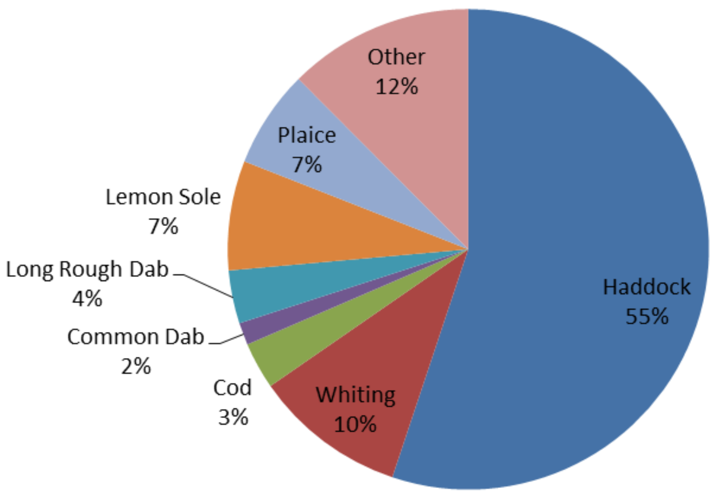

Figure 13. Catches proportion in weight of the captured species, considering all valid hauls.

A total of 7026.5 kg of fish and crustacean were captured during trials, with haddock being the dominant species by weight making up more than half of the catch (3872.9 kg). Whiting and cod represented 10% and 3% of the total catch, respectively (719.9 kg; 221.5 kg). Altogether, the most captured flatfish - plaice, lemon sole, common dab, and long rough dab - accounted for 20% of the total catch weight (1336.8 kg). Other species were caught, yet in smaller quantities and with reduced value for this experiment. All species caught and their respective weight are identified in **Appendix 2 and 3**.

The length frequencies for all main species caught are shown in **Fig.14**, along with its mean size. Haddock and whiting are the species with higher catch in number, whose size average are 17.0 cm and 21.2 cm, respectively. For cod and all flatfish, catch was not greater than 800 individuals for each species.

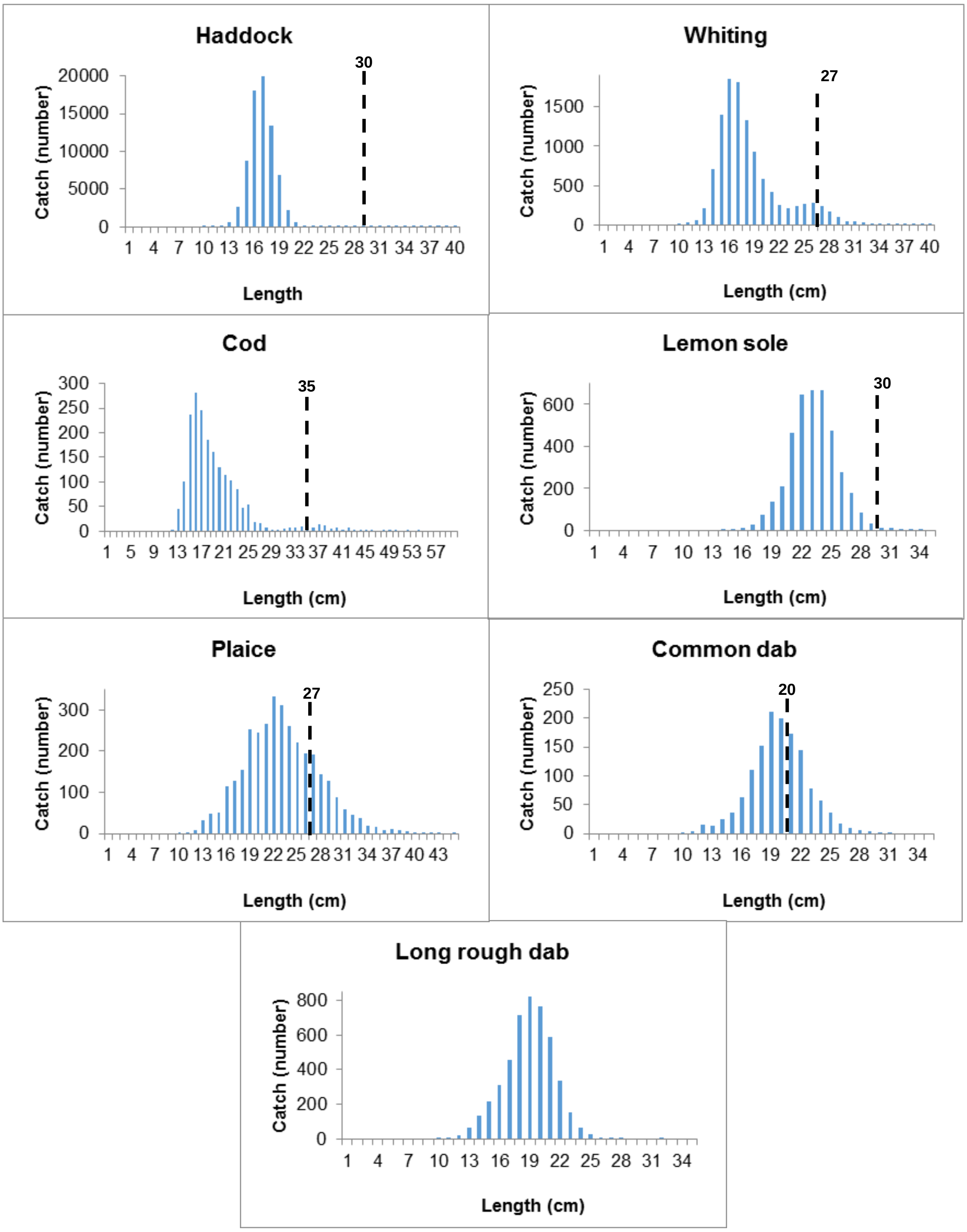

Figure 14. Length frequencies for all main species caught during trials (total catch). The thick dashed vertical line along with the label represents the MLS in the UK (in centimeters). Long rough dab does not have an established MLS.

Data analysis

The proportion of fish that went into the control codend (in weight) is shown in **Fig.15** and **Fig.16**. The Below-on gear layout is the one with the greatest amount of fish going into the control codend, in what comes to all flatfish and roundfish. Cod, lemon sole, plaice, common dab and long rough dab are the species that have the higher tendency to go through the grid to the lower codend, when the lights are on in the Below gear layout. Lemon sole and plaice display the highest percentage rate reaching 64% and 52%, respectively, and the lowest percentage results in relation to the Above gear layout. For haddock, the predominant quantity of fish goes into the control codend in the Above-on and off gear-layouts, with the Above-on layout showing greater results. As for whiting, there is an opposite reaction, comparing to haddock. The higher percentage of fish is

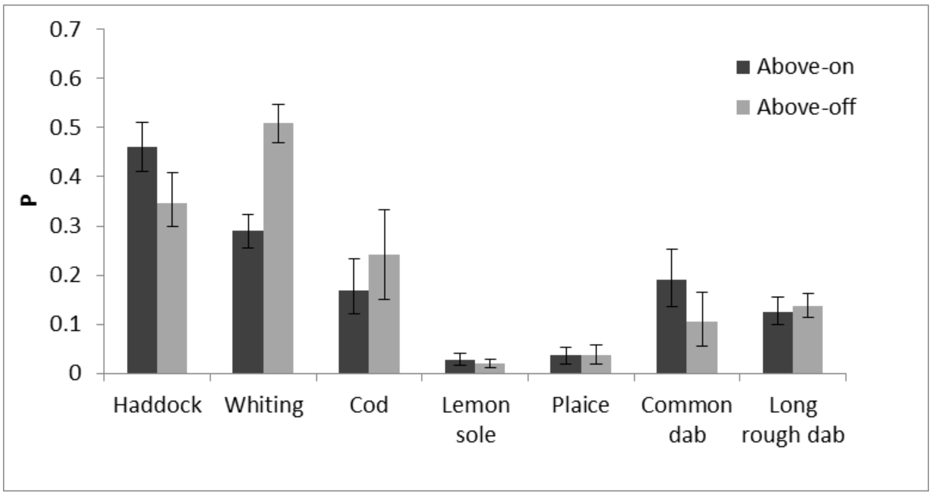

Figure 15. Weight proportion of fish in the control codend per species, in Above gear-layout used in trials. Error bars represent the confidence limits (95%).

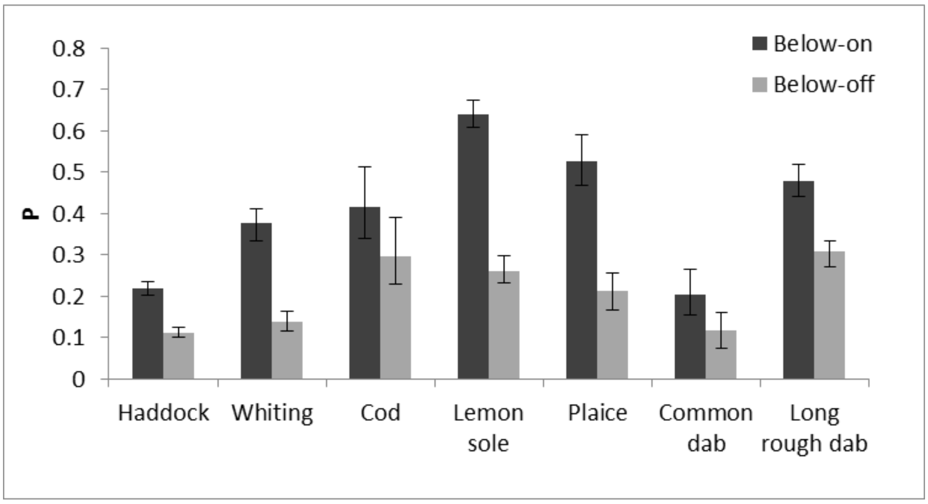

Figure 16. Weight proportion of fish in the control codend per species, in Below gear-layout used in trials. Error bars represent the confidence limits (95%).

shown in the Above-off gear layout, being the only species where this type of gear is the most represented. The plots for each species' proportion, by length class, that went into the control codend are presented in **Appendix 4**.

The mean curves of the smoothing analysis performed for haddock are shown in **Fig.17**, regarding the Below layout. When the lights are on, results demonstrate a higher proportion of small length fish going through the grid to the control codend, opposing the almost constant selectivity curve when the lights are off.

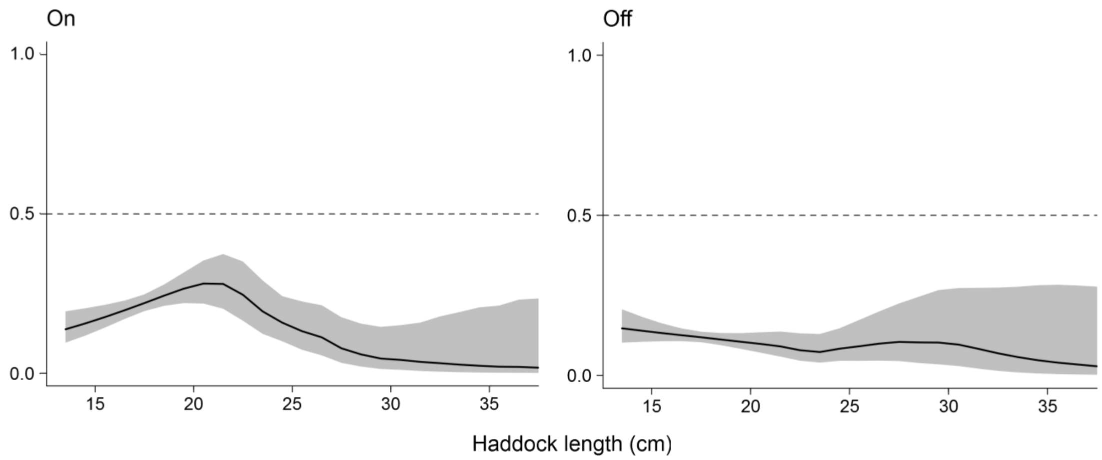

Figure 17. Mean curves of smoothing analysis for haddock, for the Below-layout. Left plot: lights on; Right plot: lights off. Grey shade represents the 95% confidence interval levels.

As for the lemon sole, the mean curves of the smoothing analysis are represented in **Fig.18**. Results show a pronounced difference among the on and off groups, with a high proportion of fish going into the control codend when the light is on and the opposite effect is observed when the lights are off.

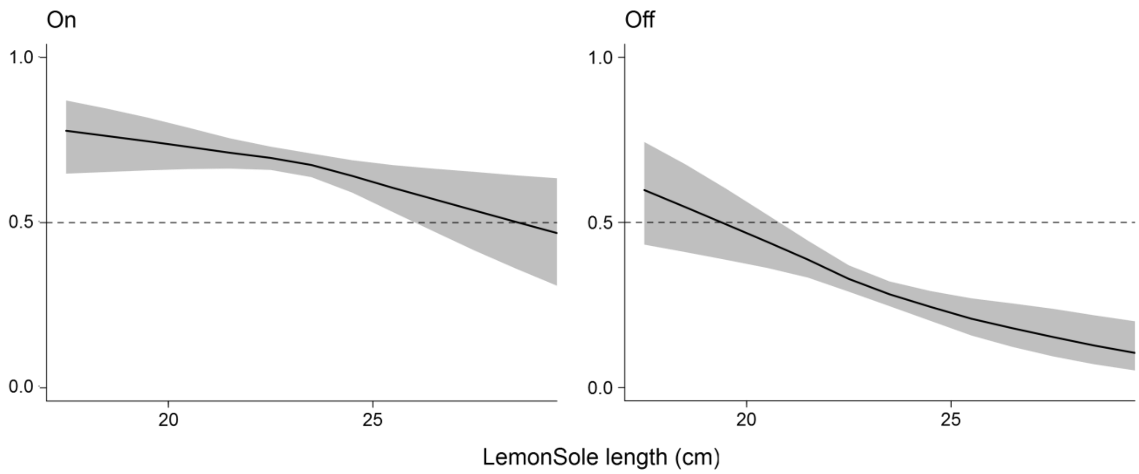

Figure 18. Mean curves of smoothing analysis for lemon sole, for the Below-layout. Left plot: lights on; Right plot: lights off. Grey shade represents the 95% confidence interval levels.

The mean curves of the smoothing analysis performed for cod are shown in **Fig.19**, also for the Below layout. When the lights are on, more fish within the length range of 27-37 cm (approximately) are caught in the control codend comparing with the same length range for when the lights are off.

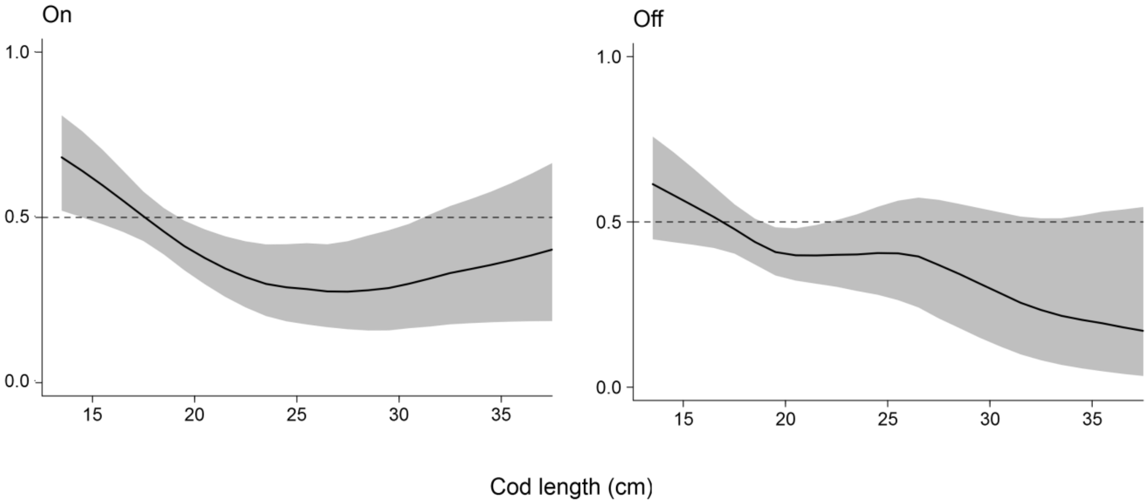

Figure 19. Mean curves of smoothing analysis for cod, for the Below-layout. Left plot: lights on; Right plot: lights off. Grey shade represents the 95% confidence interval levels.

The mean curves of the smoothing analysis performed for whiting are shown in **Fig.20**, regarding the Above layout. When the lights are off, results demonstrate a higher proportion of fish going through the grid to the control codend, meaning this species may show repulsion towards light.

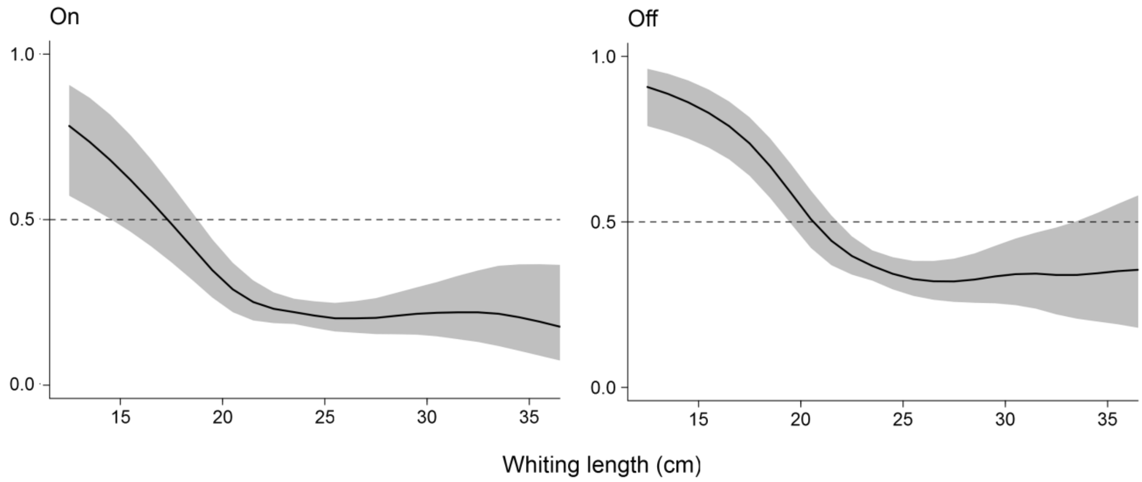

Figure 20. Mean curves of smoothing analysis for whiting, for the Above-layout. Left plot: lights on; Right plot: lights off. Grey shade represents the 95% confidence interval levels.

Discussion

Crustacean grid selectivity trial

When reviewing experiments with grids, carried out in the last few years, it is noticeable that crustacean fisheries, namely those where Norway lobster is the main target species, are among the most frequently studied. However, the selective properties of grids for other crustaceans have also been evaluated in the North-eastern Atlantic. It is the case of the rose shrimp (*Parapenaeus longirostris*) and the blue-and-red shrimp (*Aristeus antennas*) in Portuguese waters (Fonseca *et al*, 2005). Ulmestrand and Valentinsson (2003) tested a 35 mm bar-spaced grid in the Norway lobster fishing grounds of Skagerrak and Kattegat, with results indicating a substantial reduction of fish bycatch, such as cod and whiting, without compromising the overall catch of Norway lobster. In the Northern shrimp (*Pandalus borealis*) fishing grounds of the North Sea, a flexible grid system was also tested by Madsen and Hansen (2001) resulting in improved catch of Norway lobster and shrimp and leading to a noteworthy reduction in the catch of cod, whiting and haddock under the MLS. Furthermore, in the Kattegat and Skagerrak fishing grounds, Frandsen *et al* (2011) tested a new codend concept combining square meshes and diamond meshes. The method was successful and Norway lobster selectivity improved as the L_{50} increased significantly without increasing discards of other species. Due to these good results, since 2009, a new regulation of the European Union makes the use of a sorting grid to reduce bycatch of cod mandatory for all vessels targeting Norway lobster in the North Sea and Skagerrak area (Council Regulation (EC) No 43/2009). We must take into consideration that these results refer to fisheries where there is a single, or very few, target species. However, unlike fishers in the North Sea, the Portuguese crustacean-trawl fishers are interested in retaining a large diversity of commercial fish bycatch.

Experiments with grids were also carried out in other latitudes, and other selective systems. As an example, a study regarding the use of several codends with different sizes and shapes (Queirolo *et al.*, 2011) showed acceptable target species losses and a significant decrease of bycatch (7% and 48%, respectively). Other trials related to crustacean selectivity in New South Wales, Australia (Broadhurst *et al.*, 1996) included panels of square-mesh, soft mesh separating panels and a Nordmøre-grid. When using the grid, the results showed a significant reduction in by-catch (77%) with no reduction in catches of school prawns compared to a conventional codend.

For Portuguese waters, Fonseca *et al* (2007) report a significant effect of mesh size for Norway lobster ($p<0.05$) and shrimp ($p<0.001$) by testing three different mesh sizes and 2 types of twine. Also, while testing a modified Nordmøre grid similar to the one tested here in the south coast of Portugal, (Fonseca *et al.*, 2005) observed a 73-74% blue whiting bycatch reduction, but at the cost of a considerable loss of commercial crustacean species, Norway lobster (8-14.9%) and rose shrimp (3.9-9.1%).

The results reported in the current study demonstrate that it is possible to separate fish (blue whiting) from crustacean (Norway lobster) into different codends by using a sorting grid,making use of behavioural differences between species. Blue whiting displayed a strong avoidance behaviour towards the separator grid, with most of the fish swimming upward, towards the grid's opening into the upper codend. On the other hand, Norway lobster, a species known by only displaying an avoidance behaviour upon the physical contact with any component of the fishing gear was partially (about 50%) carried out passively through the lower opening of the grid, while the remainder fraction entered in contact with the grid bar section, and consequently was submitted to a size-selection. The individuals captured in the upper codend were of bigger dimensions as they were selected by the grid bars and guided to the upper opening. The observed contrasting behaviours are in line with what was observed by Fonseca *et al* (2005).

Total catches were generally low, in part due to the small duration of hauls (60 min.) compared to the usual commercial. When comparing Norway lobster selection curve parameters obtained in the present study with those in Fonseca *et al* (2005) (L_{50}=49.8; SR=9.1), there is a significant reduction of L_{50} and SR in this study (L_{50}=29.7; SR=6.6). The differences in L_{50} may be mostly attributed to bar spacing (25 mm, in the former study, versus 20 mm herein). The overall catch size may also have influenced the results. In fact, an effect of the species catch weight on the L_{50}, not present in the former study, was estimated in this study. However, the overall dataset is too limited to allow for further inference.

As for grid retention (= % escape to the upper codend) by size, we report an increase in the proportion of blue whiting being guided upwards, from about 73% in Fonseca *et al* (2005) to about 80% in this study. This is a noteworthy result, confirming that this species exhibits a strong avoidance behaviour towards the grid

Fish selectivity using artificial light

This experiment was basically directed at the evaluation of fish species reaction in relation to two different layouts where a grid installed on a horizontal panel dividing the gear into an upper and lower section was used with lights on and off. Yet, the goal consisted on reducing bycatch and discards, using light to improve selectivity by making use of behavioural differences between species.

The most captured fish was haddock, a species that has a high commercial value in Scotland. It was expected to catch bigger individuals, yet the average size of fish was 17 cm which is far below the minimum landing size (MLS=30 cm), and consequently not marketable. However, this cannot be seen as a drawback since the grid could eventually lead to an escape window or open codend, allowing the escapement of undersized fish.

The two different layouts used in the experiments were chosen based on previous knowledge on fish behavior inside the trawl (Glass *et al.*, 1989; Summerbell *et al.*, 2016). For instance, haddock and whiting go mainly to the control codend when the “Above” layout was used. On the other hand, flatfish show a higher tendency in going into the control codend when the Below layout was used. This means there is already a sorting method before even adding the artificial light to the grid; the Above layout is directed mainly to haddock and whiting and the Below layout directed to flatfish, were in both layouts the target catch is captured in the control codend.

More fish of all species passed through the grid into the control codend (when compared to the main codend) when the gear-layout was the “Below-on” one (i.e. the grid light was on), although for cod and common dab the superposition of the 95% confidence intervals indicates that average differences are not statistically significant. Lemon sole and plaice were the species showing the highest contrast between the experiments with and without lights. Approximately ~70% of the former species was retained in the control codend with lights on. This indicates that the lighted grid favoured the swimming towards the control codend passing through the grid. Flatfishes have a low swimming speed and endurance compared to roundfish and typically remain closer to the seafloor during herding (Ryer, 2008), which explains the results for the “Below-layout” category. In fact, the results for flatfishes when the grid is in the “Above-layout” is rather contrasting. Few of these fish pass through the grid and the catch in the control codend is not influenced by the lighting of the grid. Main and Sangster (1981) report that haddock usually swims up to 1 meter above the sea bed and as it gets tired it falls back and swims slowly upwards. This observation is consistent with the results of this study, as this species was caught in bigger amounts in the upper codend when the layout Above was used. Whiting is reported to swim slightly higher off the sea bed than the haddock (Main and Sangster, 1981), which may also explain the results for the Above layout. Also regarding this species and layout, results suggest that whiting may be repelled by light as it was captured in higher numbers in the control codend when the lights were off. In relation to cod, the results show there is a bigger tendency in going into the lower codend. This is also supported by Main and Sangster (1981) where they observe that this species swims typically very close to the sea floor.

Laboratory experiments with haddock demonstrated that vision is the sense which enables the fish to react in an ordered way to the stimulus of a towed net (Glass *et al.*, 1989). (Marchesan *et al.*, 2005), also in laboratory experiments aimed at investigating the effects of artificial light of different intensities and wavelengths in four Mediterranean fish species, demonstrated how changes in light properties can result in different behavioral outcomes – attraction, repulsion, or no reaction.

In recent experiments at sea using LED lights along the fishing line in a moving trawl, Hannah *et al* (2015) reported a noteworthy reduction for euchalon (*Thaleichthys pacificus*) bycatch (by 91%) and juvenile rockfishes (reaching 82%), as well as for slender sole (*Lyopsetta exilis*) and other small flatfishes (69%). The effectiveness of LED lights in bycatch reduction is higher when they are positioned near the front of the trawl, in the footrope, since this is the area where fish present more swimming ability. This study was the first successful application of artificial light in a moving trawl with the intention of reducing bycatch by making use of fish behavioural differences.

Except for this latter study, comparisons with other experiments are not possible because no additional literature regarding the improvement of fish selectivity using light could be found. There is, therefore, a strong justification for pursuing this line of research.

Both experiments had the same goal of reducing bycatch and discards by improving species and size selectivity in trawl gears. Nevertheless, the trials performed in Aberdeen with the light grid were only the initial process of a longer research on enhancing fish behaviour by using artificial light. By making use of species behaviour, either in relation to the crustacean grid or to the light grid, the results obtained demonstrate high potential in separating species in different codends or guiding them to escape windows if these systems are to be used in commercial nets. These new technologies lead to sustainable fisheries through reducing non-target species catch.

Conclusion

The implementation of the Landing Obligation under the new European Union Common Fisheries will in due course represent a paradigm change in the management of commercial stocks in the area. Together with the Marine Strategy Framework Directive the new CFP will lay down foundations for a full integration of fishing in an ecosystem management perspective, i.e. an Ecosystem-Approach to Fisheries Management (EBFM). The final goal is to maintain the overall structure and function of the ecosystem, thus surpassing the objective of sustainability of commercial relevant stocks. For that purpose, the fishing patterns will have to change, favouring gear and methods that minimized bycatches and discards.

The experiments reported in this thesis are in line with requirements above, by both evaluating a selective system designed to solve the problem of bycatch of a specific fishing fleet – the Portuguese bottom trawling targeting crustacean – and conducting research on the use of lights to enhance fish reaction in relation to a selective device.

The use of a selective grid allowing for the capture of crustaceans (Norway lobster) in a lower codend catch while fish (blue whiting) is mainly directed to an upper codend, solved a problem raised in early experiments with a similar system. In fact, in the former experiments the fish was excluded by an opening in the upper panel of the gear along with some percentage of crustaceans that also escaped from the trawl. This situation would not have been welcome by fishers, who would certainly have resented the economic loss. Consequently, the logical alternative was to find a way to collect the escaping fraction, made up by non-commercial fish bycatch and highly valuable crustaceans, and the resulting system is reported in the thesis. The excellent performance, will allow that, under commercial conditions, different mesh sizes adapted to the main species collected in each codend can be used. Furthermore, considering the strong behavioural reaction between fish and crustaceans, a square mesh window could be installed in the upper codend to allow for blue whiting escape.

The lighted grid is an innovative experiment, as it makes use of light to enhance the already known behaviour of species inside the net. Lemon sole is a species with a high commercial value in Scotland and in this study a strong reaction towards light is demonstrated. Although the results showed this system can sort species, more directed research needs to be carried out to fully appreciate the potential of using light in trawl fisheries and to examine issues such as wavelength, intensity, and flash rate.

In conclusion, the overall results presented herein are promising and imply that, by improving trawl selectivity, the stocks' growth potential can be enhanced through an efficient exploitation. Nevertheless, to gain fishers' acceptance to the use of such devices, it is essential to promote demonstration actions on board of commercial vessels in the same conditions in which fishing takes place.

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Appendix

Appendix 1. Catch in weight of all hauls during the trials on the R/V “Noruega”, in kilograms.

	Weight (Kg)															
Haul/Species	**WHB**	**COE**	**SHO**	**BRF**	**NEP**	**MKG**	**GFB**	**RAJ**	**SYC**	**SQN**	**EOI**	**GRS**	**DPS**	**NZS**	**HKE**	**SFS**
21	3.6941	1.196	0.774	0.214	3.212	0.026	0.012	0.008	0.07	0	0.934	0	0.02	0	0	0
22	0	0.64	0.928	0.218	15	0.146	0.128	0.364	1.684	1.068	0.97	0.174	0	0	0	0.298
23	0	0.958	0.032	0	11.259	0.188	0.476	0	0.37	0.034	0	0.24	0	0	0	0
25	6.916	0.096	0	0.104	0.712	0.038	0.106	0	0	0	0.428	0	0.026	0	0	0
26	0.996	0.15	0.026	0	9.804	0.076	0.018	0	0	0	0.95	0	0	0	0.248	0
27	0.904	0.312	0.044	0	8.07	0.04	0.012	0	0.042	0	1.508	0.028	0.03	0.024	0	0
28	4.846	0.11	0.026	0	10.944	0.044	0.128	0.056	0	0	1.392	0.274	0.123	0.03	1.252	0
29	6.766	0.72	0.18	0.52	1.666	0.032	0.108	0.05	0	1.098	1.542	0.03	0.098	0	1.998	0
30	96	0.574	0.92	0.144	8.1	0.056	0	11.1	1.25	0	1.572	0.166	0.038	0.034	1.962	0
31	10.7	0	0.026	0.164	15.774	0.014	0.054	0	0	0	0.802	0.016	0.018	0.028	0	0
32	0	0.088	0.01	0	6.692	0.082	0.07	0.86	0.4844	0	1.198	0	0.022	0	0	0

33	30.55	0.176	0.498	0.234	5.382	0.032	0.152	0.252	0.496	0	1.728	0.042	0.06	0.046	2.17	0.144
34	130.16	0.294	0.814	0.272	7.91	0	0.09	0.126	0.208	0	0.542	0	0	0	0.926	0
35	5.526	0.304	0.052	0	3.438	0	0.026	0.004	0.534	0	0.686	0	0.016	0	0.594	0
36	5.738	0	0.83	0.126	10.848	0.024	0.118	0	0	0	0.67	0	0.106	0.154	0.58	0.146
37	834.14	0.596	0.132	0	4.424	0	0.106	0.186	0	0	0.284	0	0.028	0	0	0.138
38	44.422	0	0	0	5.962	0	0	0	0	0	0	0.048	0	0	0.456	0
39	2.67	2.682	0	0	13.166	0.068	0.086	0.26	2.51	0	0	0	0	0	0	0
Total	349.8881	8.3	5.16	1.996	137.939	0.866	1.584	13.08	7.6484	2.2	14.922	1.018	0.557	0.316	10.186	0.588

Appendix 2. Species caught during the trials on the R/V Alba na Mara, presented and identified (Campbell and Nicholls, 2008).

Haddock (*Melanogrammus aeglefinus*)

Whiting (*Merlangius merlangus*)

Atlantic cod (*Gadus morhua*)

Plaice (*Pleuronectes platessa*)

Lemon sole (*Microstomus kitt*)

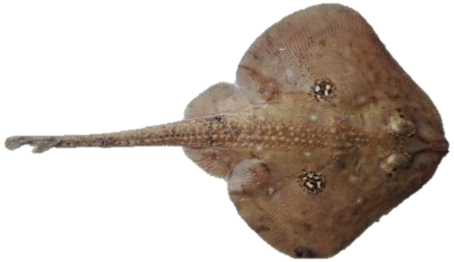
Common dab (*Limanda limanda*)

Long rough dab (*Hippoglossoides platessoides*)

Monkfish (*Lophius piscatorius*)

Herring (*Clupea harengus*)

Appendix 2. (continued).



Cuckoo ray (*Raja naevus*)

Hooknose (*Agonus cataphractus)*

Norway pout (*Trisopterus esmarkii*)

Lesser spotted dogfish (*Scyliorhinus canicula*)

Striped red mullet (*Mullus surmuletus*)

Bull-rout (*Myoxocephalus scorpius*)

European squid (*Loligo vulgaris)*

Ling (*Molva molva*)

Atlantic horse mackerel (*Trachurus trachurus)*

Appendix 2. (continued).

Dragonet (*Callionymus lyra*)

Lumpsucker (*Cyclopterus lumpus*)

Scallops (*Pecten maximus*)

Lobster (*Homarus gammarus*)

Red gurnard (*Chelidonichthys cuculus)*

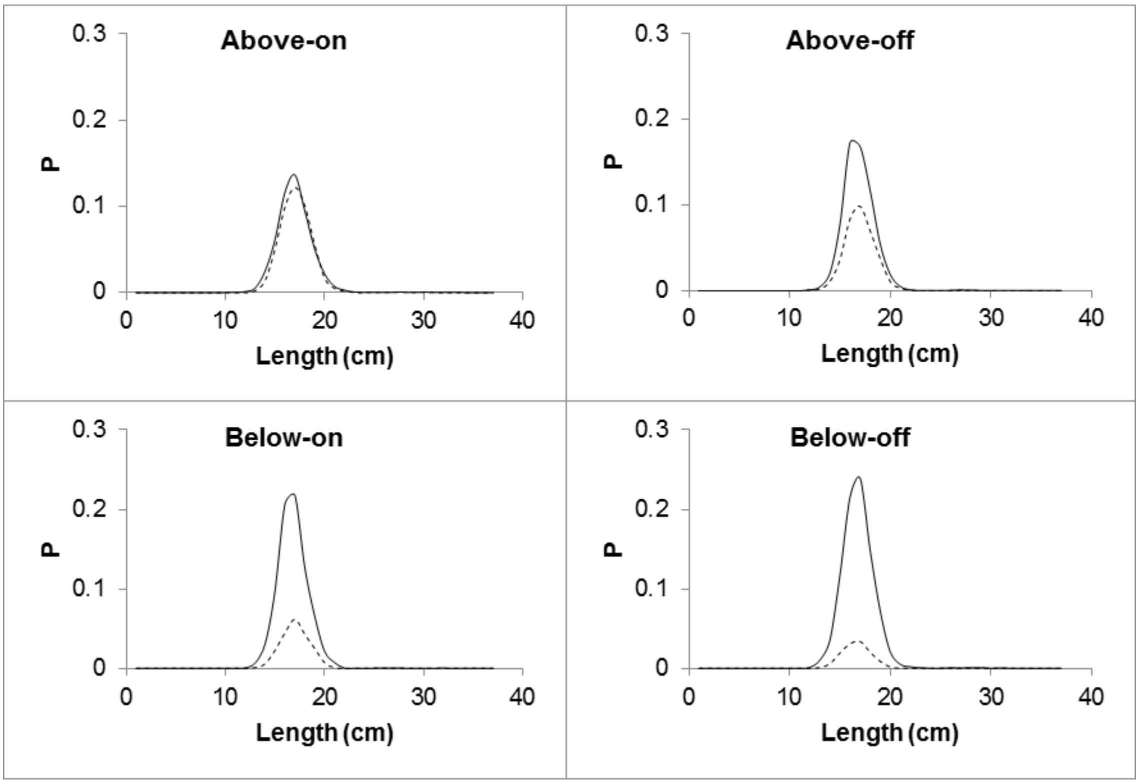
Appendix 3. Catch in weight of all valid hauls during the trials on the R/V Alba na Mara, in kilograms.

	12 hauls		13 hauls		10 hauls		11 hauls		Total
	Above-On		Above-Off		Below-On		Below-Off		
Species / Codend	**Control**	**Main**	**Control**	**Main**	**Main**	**Control**	**Main**	**Control**	
Haddock	443.54	520.83	417.2	784.27	855.69	240.78	542.3	68.27	3872.88
Whiting	50.53	123.52	110.01	106.185	125.48	75.92	110.68	17.56	719.885
Cod	12.19	60.615	17.667	55.215	21.735	15.46	27.14	11.45	221.472
Common Dab	5.94	25.228	2.962	25.33	18.54	4.775	20.015	2.666	105.456
Long Rough Dab	8.56	60.305	9.12	57.645	28.845	26.48	41.85	18.555	251.36
Witch	0.1	0.05	0	0.174	0.698	0	0.394	0.1	1.516
Lemon Sole	2.73	94.46	2.255	108.77	59.53	106.27	106.535	37.7	518.25
Plaice	5.36	141.75	4.9	127.34	40.835	45.64	75.485	20.385	461.695
Nephrops	0	0.148	0	0.116	0.166	0.056	0.156	0.02	0.662
Monkfish	0.7	3.105	1.1	10.408	8.397	1.27	13.246	0.6	38.826
Brill	0	0.108	0	0	0	0	0	0.4	0.508
Bullrout	0	3.688	0.5	3.213	3.478	1.16	3.628	0.72	16.387
Dragonet	0	0.166	0	0.06	0.05	0.316	0	0.35	0.942
Dragonet Spotted	0	0.116	0	0.104	0	0.02	0	0.25	0.49
Edible brown crab	0.14	37.09	0	24.727	5.848	24.165	8.836	42.195	143.001
Flounder	0	0	0	0	0.176	0	0	0	0.176
Four Bearded Rockling	0	0.344	0	0.34	0.344	0.26	0.241	0.742	2.271
Gurnard Grey	0.2	1.786	0.224	1.541	0.374	0.454	0.898	0.706	6.183
Gurnard Red	0	0.562	0	0.544	0.528	0.42	0.322	0.226	2.602
Gurnard Tub	0	0.896	0	0.664	0.272	0.2	0.704	0	2.736
Halibut	0	0	0	39.5	0	0	0	0	39.5
Herring	123.46	30.843	26.922	13.755	86.06	5.944	52.885	4.065	343.934
Hooknose	0.15	2.266	0.12	2.016	1.494	0.56	2.353	0.962	9.921
Horse Mackeral	0.76	1.416	1.15	0.914	0.962	0	0.772	0.2	6.174

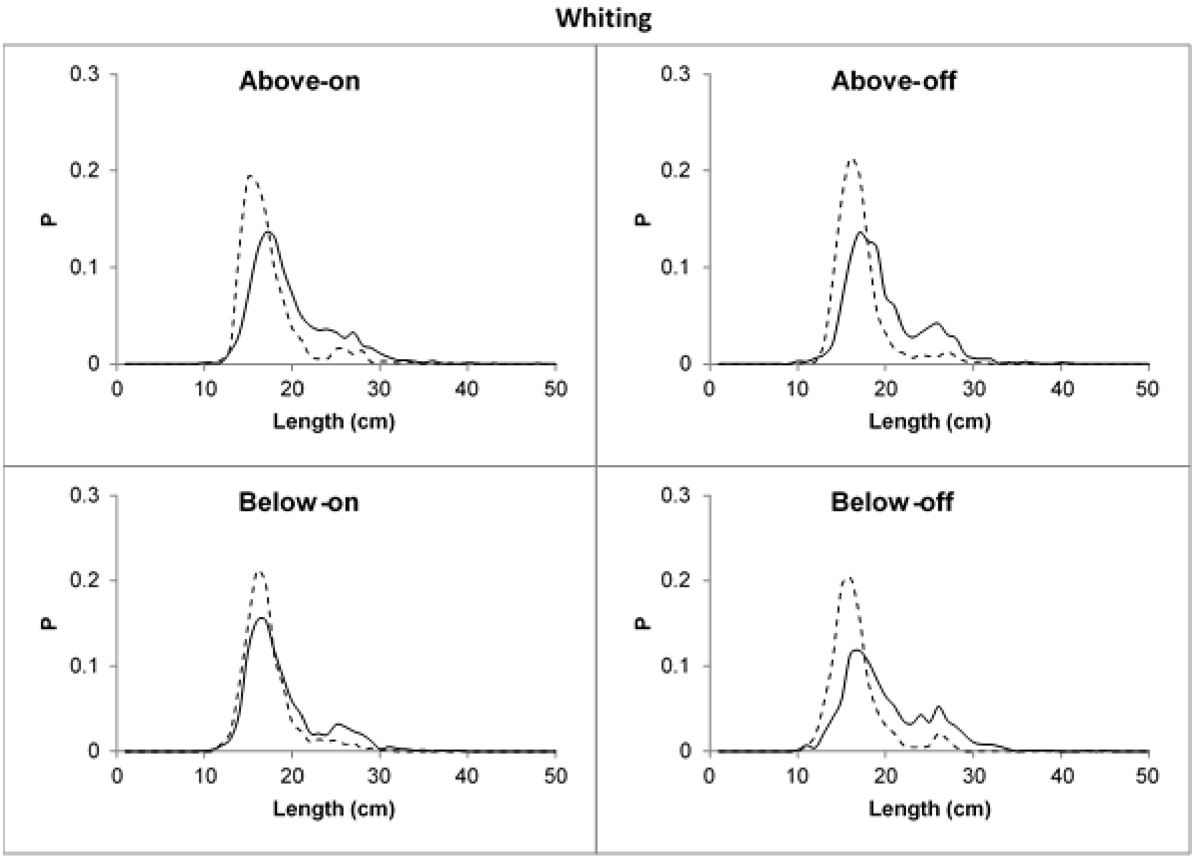
John Dory	0	0	0	0	0.142	0	0	0	0.142
LAR	0	0	0	0	0	0	0.05	0	0.05
Lesser Spotted Dogfish	0	7.325	0	2.715	0	0.99	1.69	0	12.72
Ling	0	1.29	0	0.73	0.825	0	1.88	0.248	4.973
Lobster	0	17.496	0	13.515	2.665	0.61	7.33	0.6	42.216
Lumpsucker	0	0	0	2.925	0	0	0	0	2.925
Macerel	0.6	0	0	0.4	0	0	0	0	1
N. Pout	1.746	4.054	6.906	4.503	2.824	3.544	4.355	4.26	32.192
Poor Cod	0	0	0.17	0.22	0.03	0	0	0.1	0.52
Red Mullet	0.33	0.974	0.27	2.09	0.392	0.522	0.85	1.47	6.898
Saithe	0	0.878	0.9	0	0	0	0	0	1.778
Scallops	0	10.368	0	8.023	1.116	4.345	4.031	6.91	34.793
Seabass	0	0.412	0	0	0	0	0	0	0.412
Skate - CRA	0.25	16.254	0.98	14.579	8.706	4.19	14.885	5.51	65.354
Sprat	0	0.01	0	0.01	0.01	0	0.01	0	0.04
Squid - Loligo	2.07	12.832	2.3	11.326	7.67	1.139	12.72	0	50.057
Starry smooth hound	0	0.34	0	0	0	0	0	0	0.34
Turbot	0	2.595	0	0	0	0	0.7	0	3.295
TOTAL	659.356	1184.12	605.656	1423.867	1283.882	565.49	1056.941	247.22	7026.532

Appendix 4. Length frequencies proportion in all four gear-types tested. Dark-line: main codend; dashed line: control codend.

Haddock

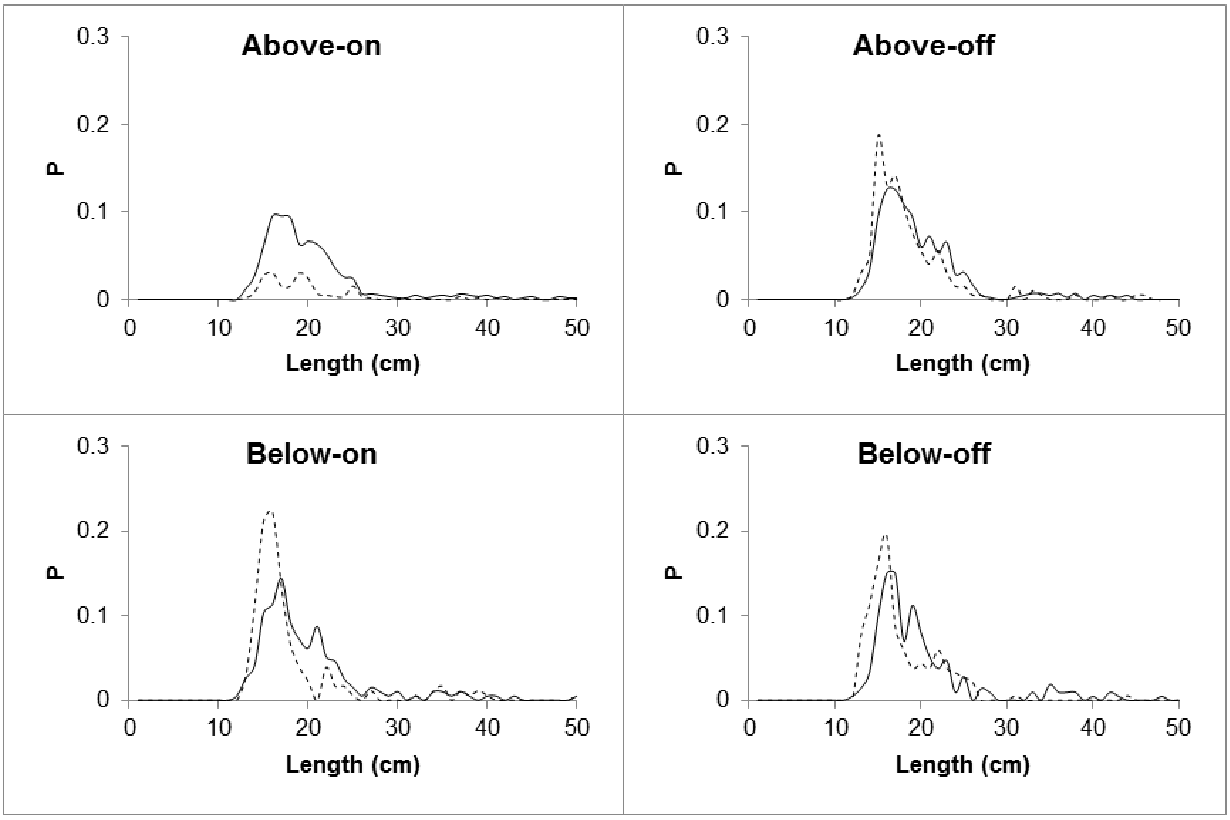


Appendix 4. (continued)



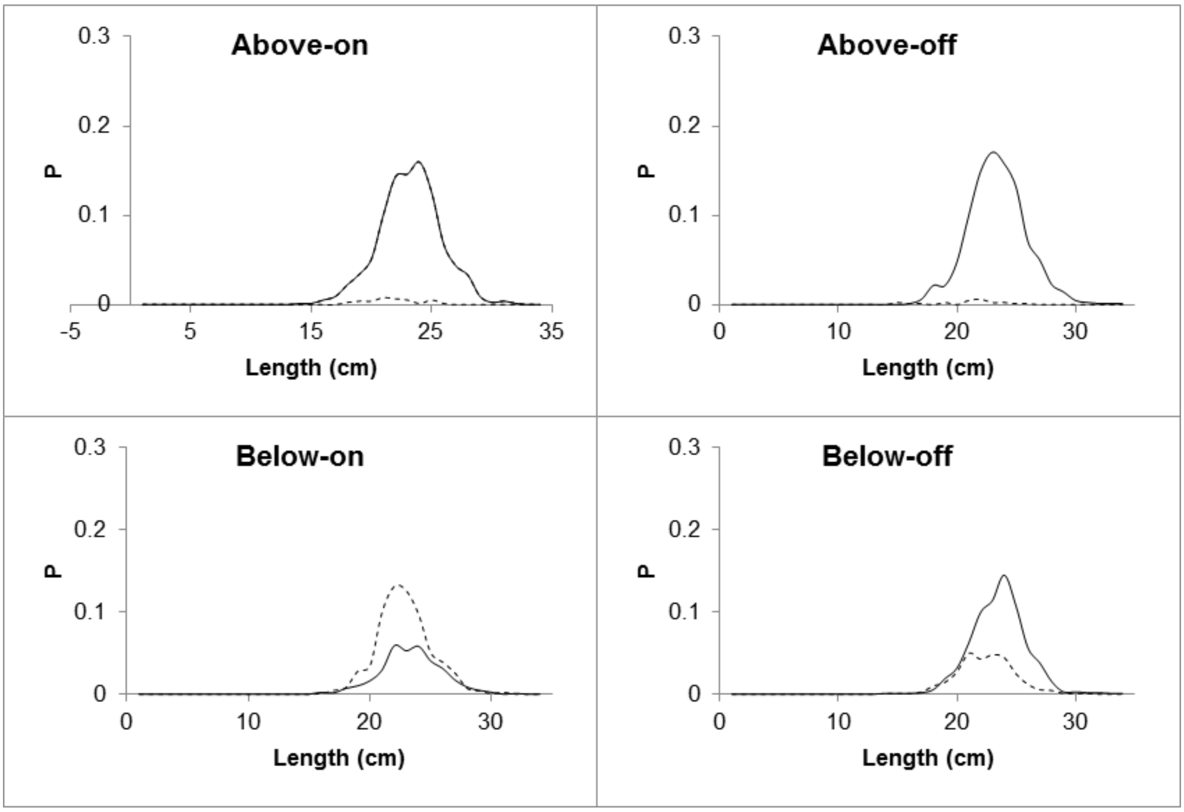
Appendix 4. (continued)

Cod



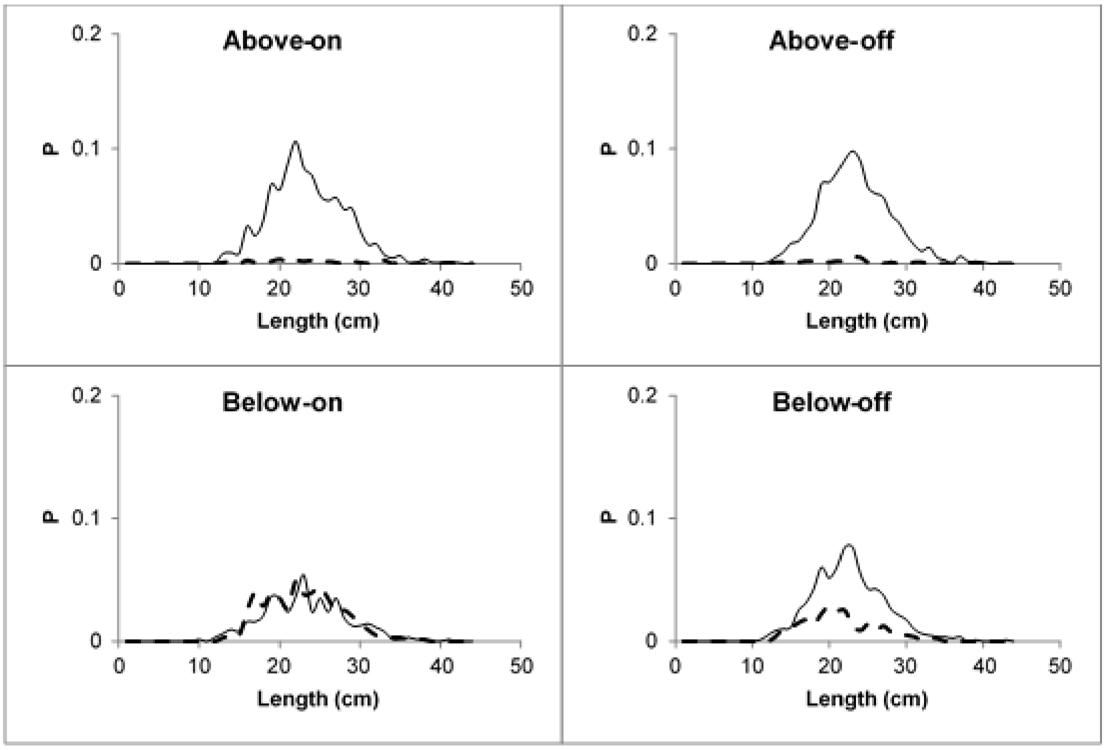
Appendix 4. (continued)

Lemon sole

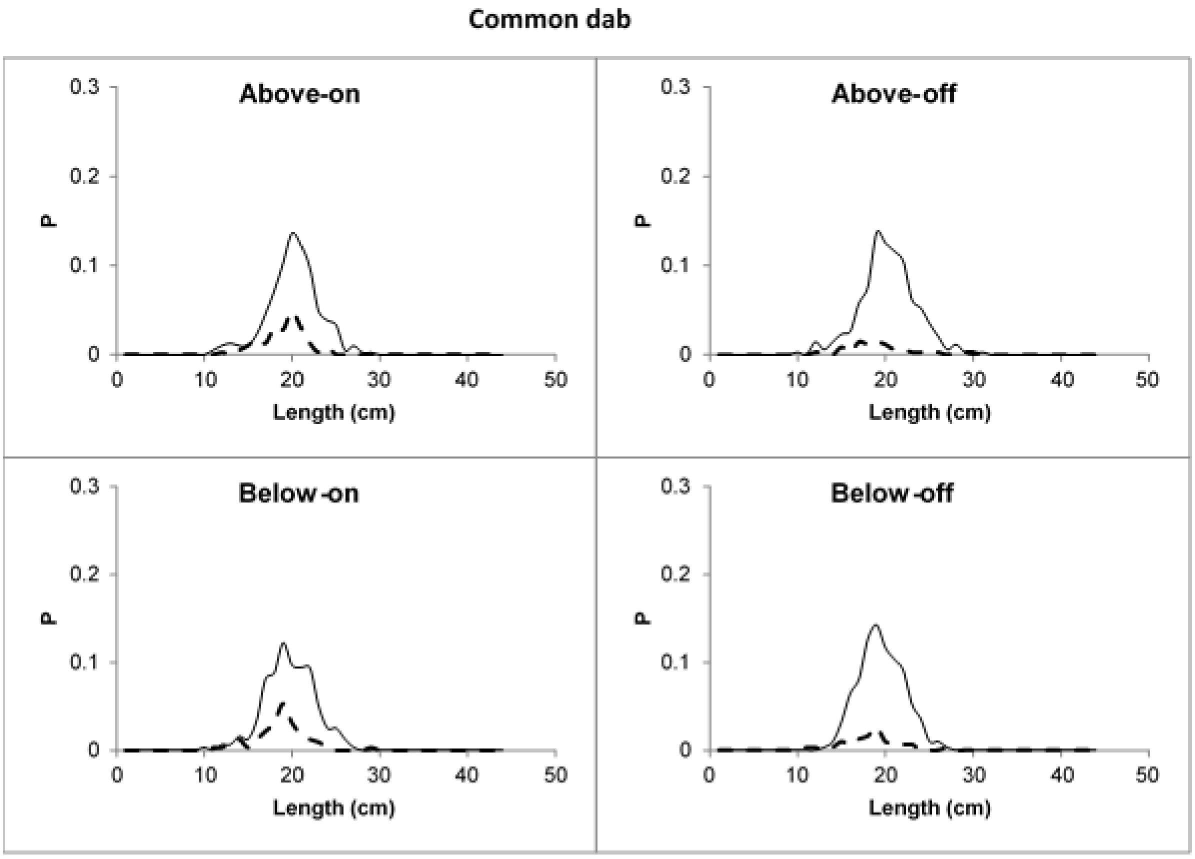


Appendix 4. (continued)

Plaice



Appendix 4. (continued)



Appendix 4. (continued)