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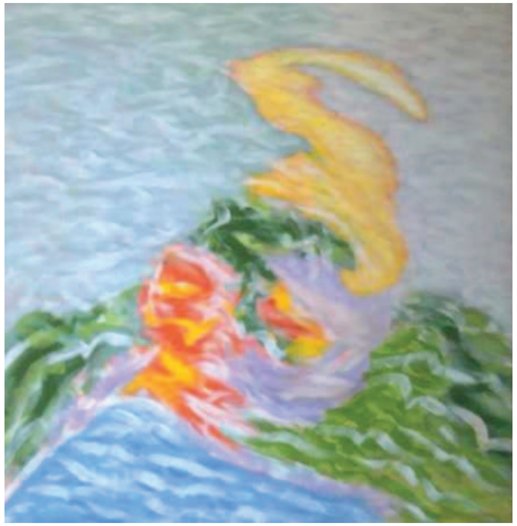

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- “The figure arises out of the sea, on to dry land, and into the unknown.”

The estimation and improvement of the selectivity in crustacean and fish trawls

Aida Campos
Instituto Nacional de Investigação Agrícola e das Pescas (INIAP/IPIMAR)

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Ao André
e à Margarida

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This work, as most similar studies, involved the collaboration of a high number of persons.

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Abstract

Scientific evidence points to the overfishing of some of the most important commercial stocks exploited in Portuguese waters (ICES sub-area IXa) by the bottom trawling fleets targeting fish and crustaceans. While temporary fishing interdiction has been implemented in specific areas off the south-west coast, in an attempt to reduce the fishing effort upon juvenile fish, there has been considerable resistance to the introduction of gear modifications, including the increase in cod end mesh sizes. The small cod end mesh sizes currently in use, particularly in crustacean trawling, largely contribute to catch discarding or misreporting, causing increasing conflicts between trawl fishermen and fishermen from other *métiers* competing for common resources.

Recent studies have shown that discard rates can attain very high levels, up to 70% on board of both crustacean and fish trawlers off the Portuguese south coast, with a high number of low-valued species, especially small pelagics, being discarded in large amounts.

A number of gear modifications were tested in crustacean and fish trawls, aiming at reducing the amount of undersized fish from the target species and allowing for the escapement of a significant fraction of non-commercial by-catch. Their usefulness is discussed in a review, six papers and an overview of the thesis.

The improvement of size-selectivity, by increasing cod end mesh size and changing mesh configuration was addressed for the deep groundfish assemblage off the south coast exploited by crustacean trawlers (Papers I and II), and for the shallow and deep groundfish assemblages off the south west coast, where a number of fish trawlers usually operate (Papers III and IV). Cod end selectivity parameters for three different mesh sizes and two mesh configurations, diamond and square mesh, were estimated for a large number of target and by-catch species. In a number of cases, the data structure allowed for the analysis of between-haul variation, and selectivity models were proposed which relate the estimated parameters to the variables under test and also to external variables such as cod end catch and trawling depth, giving a first insight into the mechanisms involved in cod end size selectivity.

By-catch reducing devices (BRD's) placed in the rear part of the trawls or in the cod end, comprising different combinations of oblique separator panels in association with square mesh windows, and square mesh windows alone, were tested in crustacean fishing grounds off the south coast (Papers V and VI), with the purpose of excluding the non-commercial by-catch. The effectiveness of the different BRD's was separately evaluated for the most captured species. Between-species differences in behaviour towards the sorting devices are discussed. Size-dependence in escapement through the square mesh windows was recorded for a number of species, and the window selectivity could then be separately estimated.

The cod end selectivity experiments carried out for crustacean trawling suggested that an increase in cod end mesh size from the current 55 mm to 70 mm diamond mesh, without changing cod end design or material, would be advisable in order to reduce the amount of undersized catch. Such an increase would simultaneously allow for the exclusion of a large fraction of non-commercial by-catch. The results obtained for fish trawling provide, on the other hand, evidence of the difficulty in managing a number of target species of different shapes and sizes based only on mesh size or mesh configuration regulations.

The use of BRD's greatly contributed to the exclusion of non-commercial by-catch. While evidence of active escape behaviour through the square mesh windows was found for some by-catch species, for others the exclusion from the trawl relied on previous guidance to upper trawl areas by the separator panels used. Overall, the results suggest a significant potential for the use of by-catch reducing devices in this fishery.

Resumo

Existem evidências científicas apontando para uma sobrepesca dos mananciais mais importantes explorados, em águas nacionais (sub-área IXa do ICES), pelas frotas de arrasto de peixe e crustáceos. A interdição temporária à pesca foi implementada em áreas específicas na costa sudoeste, numa tentativa de reduzir o esforço de pesca sobre os juvenis. Por outro lado, a introdução de alterações às redes de arrasto, incluindo o aumento da malhagem no saco, tem sido alvo de uma resistência generalizada. As malhagens reduzidas correntemente utilizadas, particularmente no arrasto para crustáceos, têm contribuído largamente quer para a prática de rejeições, quer para a fuga à lota, contribuindo para a existência de conflitos crescentes entre os pescadores do arrasto e outros grupos que competem pelos mesmos recursos.

Recentemente, tem sido largamente comprovado que a percentagem de rejeições pode atingir níveis muito elevados, até cerca de 70%, a bordo de arrastões de crustáceos e de peixe na costa algarvia, onde é rejeitado um grande número de espécies sem valor comercial, correspondendo, na sua maior parte, a pequenos pelágicos.

Neste trabalho, foi testado um conjunto de modificações em redes de arrasto utilizadas na captura de crustáceos e de peixes, com os objectivos de reduzir as capturas de juvenis das espécies-alvo e permitir o escape de uma fracção significativa das capturas acessórias sem interesse comercial. A utilidade destas alterações na minimização das capturas acessórias e das rejeições, é discutida ao longo dos seis papers e dos dois capítulos introdutórios que compõem esta tese.

As consequências do aumento da malhagem e da alteração da configuração da malha do saco na selectividade intra-específica foram estudadas para a associação de espécies característica do talude continental na zona sul da costa Portuguesa, explorada pelos arrastões de crustáceos (Papers I e II), bem como para as associações características da plataforma e do talude na zona sudoeste (Papers III e IV), onde opera durante a maior parte do ano um conjunto de arrastões dedicados ao arrasto de peixe. Foram estimados parâmetros de selectividade para sacos de três malhagens diferentes e duas configurações da malha, em losango e em quadrado, para diversas espécies-alvo e espécies acessórias nas pescarias em estudo. A estrutura dos dados permitiu, para um número considerável de casos, a análise da variação entre lances, sendo propostos modelos de selectividade que relacionam os parâmetros de selectividade estimados com as variáveis testadas e com outras variáveis como a quantidade de captura no saco e a profundidade de arrasto, constituindo uma primeira abordagem, para estas pescarias, dos mecanismos envolvidos na selectividade de sacos.

Foi testado, em fundos de pesca de crustáceos na costa sul, um conjunto de dispositivos de selecção (“BRD’s”), instalados na zona posterior da rede ou no saco, compreendendo várias combinações de painéis separadores associados a janelas em malha quadrada, ou janelas funcionando isoladamente (Papers V e VI), com o objectivo de excluir espécies acessórias sem valor comercial. A sua eficiência foi avaliada para as espécies mais capturadas, sendo discutidas diferenças entre espécies no comportamento face a estes dispositivos. Foram registadas, em alguns casos, variações no escape através das janelas relacionadas com o comprimento dos indivíduos, que permitiram a estimação de parâmetros de selectividade.

Os resultados obtidos no estudo da selectividade em sacos sugerem que, para o arrasto de crustáceos, seria desejável um aumento da malhagem de 55 mm, actualmente utilizada, para 70 mm. Este aumento de malhagem, mantendo constantes o diâmetro e o tipo de material utilizado na confecção do saco, permitiria reduzir as capturas de crustáceos abaixo do tamanho mínimo de desembarque, permitindo simultâneamente a exclusão de uma fracção considerável das capturas acessórias não comerciais.

Em contrapartida, no arrasto dirigido aos peixes, os resultados obtidos põem em evidência a dificuldade em gerir, com base no aumento da malhagem ou na alteração da configuração da malha, uma pescaria onde é capturado um grande número de espécies-alvo com diferentes características morfológicas.

A utilização de dispositivos de selecção contribuiu grandemente para a exclusão das capturas acessórias sem valor comercial. Enquanto que algumas espécies evidenciaram um comportamento activo de escape através das janelas em malha quadrada, para outras, a exclusão através da janela dependeu da utilização de painéis separadores que conduziram as capturas para a secção superior da rede, promovendo o escape. Globalmente, os resultados obtidos sugerem a existência de um potencial na utilização de dispositivos selectivos nesta pescaria.

Aim of the study and list of papers

The main objectives of this study were:

1) To test the effects of increases in cod end mesh size and changes in mesh configuration on the selectivity for a number of fish and crustacean species commonly captured off the Portuguese coast, and to estimate cod end selectivity parameters for the cod ends used taking into account between-haul variation in selectivity;
2) To analyse between-haul variation and to look for possible effects of other variables on selectivity, giving a deeper insight into the mechanisms involved in cod end escapement;
3) To examine the utility of several by-catch reduction devices based on differences in behaviour between crustaceans and fish species, such as separator panels and square mesh windows, in the exclusion of the undesirable by-catch in crustacean trawls without affecting the catch of target species.

These questions have been addressed within a review, six papers, and an overview of the thesis. The papers are referred to in the text by their Roman numerals. Papers I, II and IV were reprinted with permission from Elsevier Science.

Paper I.
Campos, A., Fonseca, P., Erzini, K., 2002. Size selectivity of diamond and square mesh cod ends for rose shrimp (*Parapenaeus longirostris*) and Norway lobster (*Nephrops norvegicus*) off the Portuguese south coast. Fish. Res., 58, 281-301.

Paper II.
Campos, A., Fonseca, P., Erzini, K., 2003. Size selectivity of diamond and square mesh cod ends for four by-catch species captured in the crustacean fishery off the Portuguese south coast. Fish. Res., 60, 79-97.

Paper III.
Campos, A., Fonseca, P.. Selectivity of diamond and square mesh cod ends for horse mackerel (*Trachurus trachurus*), European hake (*Merluccius merluccius*) and axillary seabream (*Pagellus acarne*) in the shallow groundfish assemblage off the Portuguese South-west coast. Sci. Mar. (in press).

Paper IV.
Campos, A., Fonseca, P., Henriques, V.. Size selectivity for four fish species of the deep groundfish assemblage off the Portuguese southwest coast: evidence of mesh size, mesh configuration and cod end catch effects. Fish. Res. (in press).

Paper V.
Campos, A., Fonseca, P. (submitted). Evaluation of separator panels and square mesh windows as by-catch reduction devices in the Algarve (South Portugal) crustacean trawl fishery.

Paper VI.
Campos, A., Fonseca, P. (manuscript). Reduction of unwanted by-catch in the Portuguese crustacean trawl fishery through the use of square mesh windows placed in the cod end and trawl belly.

In the Review, some of the main factors affecting escapement at cod ends are discussed and their impact on cod end selectivity is closely examined. A number of trawl modifications in order to improve species or size selectivity is presented, and their utility as by-catch reduction devices is discussed. Survival of fish escaping through cod ends or modified trawls is briefly addressed.

The Overview is a general framework for the thesis. At the same time, several aspects of the methodology are addressed that were not discussed at the different papers. Overall results and discussion are presented.

In Papers I to IV, the cod end size selectivity of a number of mesh sizes (including the currently used mesh sizes) and two mesh configurations, diamond and square mesh, was estimated for the most captured crustacean and fish species in the deep and shallow fish assemblages of the Portuguese continental coast. In Papers I, II and IV the underlying causes of between-haul variability in selectivity are investigated, and selectivity models are proposed which relate the selectivity parameters estimated with the variables under test, as well as with other variables potentially responsible for between-haul variation, giving a first insight into the mechanisms involved in cod end selectivity. The utility of several by-catch reduction devices (BRD's), including separator panels associated to square mesh windows, and square mesh windows alone, for the exclusion of the non-commercial by-catch in crustacean trawling off the south coast is examined in Papers V and VI.

Review of trawl selectivity

Aida Campos

IPIMAR, Portuguese Institute for Fisheries and Sea Research, Avenida de Brasília, 1449-006, Lisbon, Portugal

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1. Introduction

Trawl selectivity has been traditionally improved by the establishment of minimum cod end mesh sizes, based on the assumption that adult fish of a particular species or group of species should be retained, while juveniles should be released, and cod end mesh size regulations are still the basis for the control of the exploitation pattern in most trawl fisheries management programmes (Armstrong et al., 1990; Caddy, 1999). However, experience has shown that the increase in cod end mesh size, when considered separately from other measures, can be of limited use due to a number of different reasons (Van Marlen, 1991; Stewart, 1993). It has been long recognized that mesh size is just one of many parameters affecting fish escapement through cod ends. Moreover, it was found that trawl selectivity can also be manipulated by changing gear design in order to separate or exclude species during the catch process, based on their different sizes, body shapes and behavioural responses to the different trawl components, which can be particularly useful in multispecies fisheries.

2. Factors affecting cod end selectivity

2.1. Mesh size and mesh shape

Cod end mesh size effects on selectivity have long been reported and became a focus of research since the late 1950s. There is a vast literature on this subject, reviewed by a number of authors (see Holden (1971) and Wileman (1988, 1991) for general reviews; and Briggs (1986) for a review on Norway lobster selectivity). Escapement through cod end meshes has generally been reported to increase with mesh size for a large number of species differing in their morphological traits.

However, evidence exists since earlier studies that a high number of other variables besides mesh size can affect the retention process in cod ends, and from the mid-to-late 1970s increasing effort has been put into the study of other characteristics influencing cod end selectivity. Mesh configuration proved to be one of the most important variables, since escapement through cod end meshes is determined to a large extent by the way the fish shape adapts to mesh shape. Square meshes, which can be obtained from normal diamond mesh netting by mounting it in such a way that the main axis of the netting deviates 45º from its original position, do not close under tension, giving most fish a better chance to escape.

The selectivity of standard diamond mesh cod ends has been compared with that of square mesh ones of similar mesh size in a large number of studies (Table 1). The observed differences in selectivity between the two mesh configurations can fluctuate considerably depending on both the species under study and the range of mesh sizes tested, being more evident for larger mesh sizes than for small mesh cod ends below 50 mm. However, higher selective properties have generally been reported in square mesh cod ends both for crustaceans such as the Norway lobster (*Nephrops norvegicus*), the rose shrimp (*Parapenaeus longirostris*) and the red shrimp (*Aristeus antennatus*), and for round or elliptical cross-sectional shaped fish such as haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), cod (*Gadus morhua*), saithe (*Pollachius virens*), herring (*Clupea harengus*), the European hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesistius poutassou*) and red mullet (*Mullus barbatus*), among others. In contrast, for those species of more flat cross-sectional shape, including the American plaice (*Hippoglossoides platessoides*), the sole (*Solea solea*), the four-spot megrim (*Lepidorhombus boscii*) and, to a lesser extent, the pout (*Trisopterus luscus*) and the seabreams (axillary seabream *Pagellus acarne* and annular seabream *Diplodus annularis*), for which the body shape is better adapted to a diamond mesh configuration, the use of square mesh cod ends has been observed to have the opposite effect of reducing L_{50}.

As observed in Table 1, variations in L_{50} are not followed by similar variations in SR, the selection range. Crustaceans are an exception, the increase in L_{50} when using square mesh being found to be generally associated to corresponding increase in SR, indicating lower retention at the same size and selection across a wider range of length classes in square mesh cod ends. For both round and flatfish, higher L_{50} estimates in square mesh cod ends may be associated either to an increase in SR, or decrease in this parameter.

A small number of experiments have been carried out where the effects on selectivity of other cod end mesh configurations such as hexagonal mesh were tested. Such effects were less conclusive, as illustrated for herring in the Baltic trawl fishery, for which higher selectivity is reported by Shevtsov (1988) when using hexagonal meshes, while Suuronen et al. (1991) reported significantly higher retention of small fish when using this mesh configuration when compared to diamond mesh of similar mesh size.

2.2. Twine characteristics and cod end construction

Similarly to cod end mesh size effects, differences in selectivity related to cod end materials have been addressed since the 1950’s, and the higher selective properties of polyamide cod ends intensively reported when these cod ends were compared with similar ones made in natural materials or in polyethylene (see Holden, 1971, for a review). However, few studies were carried out where the differences found in

Table 1.
Comparison of the selectivity parameters L_{50} and SR in diamond and square mesh cod ends for different species. Cod end mesh sizes are in mm. L_{50} and SR are in total length (cm) for fish species and carapace length (mm) for crustaceans. C - Covered cod end; HC - Hooped covered cod end; TR - Trouser trawl.

Area	Experimental conditions	Species	Selectivity parameters				Reference
			Diamond mesh		Square mesh		
			L_{50}	SR	L_{50}	SR	
Scotland	C 65mm	*Nephrops*	17.1	17.1	39.3	19.0	Robertson et al., 1986
North Sea	C 70mm D vs.60mm S	*Nephrops*	26.4	11.5	40.1	13.4	Larsvik and Ulmestrand, 1992
Aegean Sea	C 20mm	*Nephrops*	22.8	9.5	24.1	5.9	Stergiou et al., 1997
South Portugal	HC 55mm	*Nephrops*	27.1	6.1	34.7	16.0	Paper I
	HC 55mm	Rose shrimp	21.8	5.7	27.1	9.3	
South Portugal	HC 55mm	Red shrimp	13.8	22.6	32.3	9.1	Paper II
Scotland	C 90mm	Haddock	23.3	5.7	28.6	5.0	Robertson, 1983
Canada	TR 130mm	Haddock	45.8	5.5	47.1	5.7	Cooper and Hickey, 1987
Canada	TR 130mm	Haddock	46.5	6.8	51.8	4.2	Cooper and Hickey, 1989
Scotland	C 80mm	Haddock	21.2	7.4	26.4	6.5	Robertson and Stewart, 1988
	C 85mm		20.4	10.6	30.2	5.9	
Norway	TR 135mm	Haddock	47.0	3.5	49.0	3.6	Isaksen and Valdemarsen, 1988
Canada	TR 130mm	Haddock	41.7	8.5	49.6	4.9	Halliday et al., 1999
Scotland	C 90mm	Whiting	24.5	6.7	32.8	5.3	Robertson, 1983
Scotland	C 80mm	Whiting	27.1	7.6	30.8	8.8	Robertson and Stewart, 1988
	C 85mm		26.7	10.0	36.5	9.8	
Norway	TR 135mm	Cod	49.2	3.6	54.0	4.0	Isaksen and Valdemarsen, 1988
Canada	TR 130mm	Cod	58.7	4.5	59.7	4.6	Cooper and Hickey, 1987
Canada	TR 140mm	Cod	56.2	8.1	61.4	7.6	Cooper and Hickey, 1989
	TR 155mm	Cod	61.3	6.2	65.0	6.0	
Canada	TR 130mm	Cod	49.5	11.2	56.0	6.7	Halliday et al., 1999
Canada	TR 130mm	Cod	49.5	11.2	56.0	6.7	Halliday, 2002
	TR 140mm	Saithe	46.4	7.3	58.5	5.5	Cooper and Hickey, 1989
Baltic Sea	C 36mm	Herring	15.2	-	16.3	-	Dahm, 1991
	C 42mm	Herring	16.9	-	17.7	-	
Finland	TR 36mm	Herring	15.6	3.5	16.2	1.6	Suuronen and Millar, 1992
SW Portugal	C 65mm	Hake	16.6	6.0	30.9	8.8	Fonseca et al., 1993
Aegean Sea	C 20mm	Hake	13.8	7.1	15.1	5.7	Petrakis and Stergiou, 1997
South Portugal	HC 55mm	Horse mackerel	18.0	3.8	21.7	5.0	Paper II
SW Portugal	C 60mm	Horse mackerel	14.4	3.3	21.9	8.3	Paper III
Aegean Sea	C 20mm	Blue whiting	21.2	4.1	17.0	4.4	Petrakis and Stergiou, 1997
South Portugal	HC 55mm	Blue whiting	23.0	3.7	30.2	4.5	Paper II
Aegean Sea	C 36mm	Red mullet	11	1.8	11.8	1.6	Tokaç et al., 1998
	C 40mm	Red mullet	12.2	2.2	13.2	1.9	
	C 44mm	Red mullet	13.5	2.7	14.7	2.9	

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Table 1 (continued from previous page).
Comparison of the selectivity parameters L_{50} and SR in diamond and square mesh cod ends for different species. Cod end mesh sizes are in mm. L_{50} and SR are in total length (cm) for fish species and carapace length (mm) for crustaceans. C - Covered cod end; HC - Hooped covered cod end; TR - Trouser trawl.

Area	Experimental conditions	Species	Selectivity parameters				Reference
			Diamond mesh		Square mesh		
			L_{50}	SR	L_{50}	SR	
Canada	TR 130mm	American plaice	31.1	7.3	30.5	4.2	Walsh et al., 1992
	TR 140mm	American plaice	38.4	9.6	30.5	4.0	
	TR 155mm	American plaice	38.2	8.4	32.3	3.2	
Belgium	C 75mm	Sole	20.6	5.6	20.3	4.8	Fonteyne and M'Rabett, 1992
			22.9	5.3	22.4	6.5	
Aegean Sea	C 20mm	Four-spot megrim	10.3	3.3	8.5	3.5	Petrakis and Stergiou, 1997
SW Portugal	HC 65mm	Four-spot megrim	16.7	3.5	16.0	2.8	Paper IV
Aegean Sea	C 20mm	Pout	13.7	5.5	11.9	6.0	Petrakis and Stergiou, 1997
Aegean Sea	C 36mm	Annular sea bream	7.6	1.4	7.5	2.1	Tokaç et al., 1998
	C 40mm	Annular sea bream	8.6	1.2	8.8	1.5	
	C 44mm	Annular sea bream	9.9	1.1	8.8	1.1	
	C 48mm	Annular sea bream	12.7	1.3	12.0	2.2	
	C 36mm	Axillary sea bream	10.6	2.2	10.4	2.3	
	C 40mm	Axillary sea bream	11.8	1.6	12.4	1.8	
	C 44mm	Axillary sea bream	14.2	1.4	13.0	2.0	

selectivity can be attributed to cod end material only, since in most of them cod end design and mesh size, twine diameter and twine construction, which can affect cod end selectivity due to their influence on mesh opening, were found to vary simultaneously. A recent study by Tokaç et al. (2002), where the selectivity of similar cod ends only differing in the material (polyamide vs. polyethylene) was compared for several Mediterranean species, reports higher L_{50} for polyamide cod ends.

The effects of netting and twine characteristics on selectivity have been more recently reviewed by Ferro and O'Neill (1994). Mechanical effects affecting mesh shape and mesh opening are reported to be dependent on twine material, as well as on twine diameter and construction. These variables are also likely to change the water flow inside the cod end, which in turn can affect escape responses of fish or passive wash-out through cod end meshes. While the increase in twine diameter and the use of braided, instead of twisted twines, had already been reported to reduce the selectivity (Isaksen et al., 1990), adverse effects of increasing twine diameter were also found in more recent studies by Lowry (1995), Lowry and Robertson (1996), Kynoch et al., (1999) and Özbilgin et al. (2002) in polyethylene cod ends, where they are reported to reduce mesh opening due to an increase in flexural stiffness.

Mechanical effects affecting mesh shape and mesh opening are pointed out by Ferro and O'Neill (1994) to be highly related to several aspects of cod end construction, such as the length of the cod end extension, the number of meshes in cod end circumference and the use of lastridge ropes. This was demonstrated in a number of studies for diamond mesh cod ends (Table 2). Because diamond meshes, in the rear net sections, tend to close under tension as the catch bulk increases, reducing the cod end extension was found to contribute to an increase in cod end mesh opening, increasing the escape probability of fish. A similar effect can be attained by using narrow cod ends with a lower number of meshes in circumference, or using shortened lastridge ropes. While the effects of these variables on selectivity have been mainly investigated for round-bodied fish, species that are more flat in cross-sectional shape do not seem to profit, as expected, from increase in cod end mesh opening related to such cod end alterations, as suggested by the selectivity data for annular seabream (Lök et al., 1997) in Table 2.

Table 2.
Relationship between L_{50} (in cm) and cod end extension length, cod end diameter and length of lastrige ropes. Cod end mesh sizes are in mm. C - Covered cod end; HC - Hooped covered cod end; TR - trouser trawl; TW - twin trawl.

Area	Experimental conditions	Species	Extension length (m)			Reference
			Long	**Short**	**Standard**	
North Sea	C 80mm	Haddock	19.4	26.0		Robertson and Ferro, 1988
		Whiting	25.9	30.3		
			18.5	**13.9**	**12.1**	
Baltic Sea	C 42mm	Herring	17.2	17.7	19.5	Dahm, 1991
			13.7	**9.1**	**no ext.**	
North Sea	C 80mm	Haddock	20.1	21.4	23.9	Reeves et al., 1992 (1)
	2.2m diameter	Whiting	23.6	25.3	28.7	
		Cod	21.4	22.2	23.6	
			Cod end diameter (m)			
			Standard	**Narrow**		
North Sea	C 80mm	Haddock	20.2	23.2		Robertson and Ferro, 1988
	C 90mm	Whiting	26.7	31.2		
			4.0	**3.2**	**2.2**	
North Sea	C 80mm with no extension	Haddock	16.5	19.8	23.9	Reeves et al., 1992 (1)
		Whiting	21.5	24.7	28.7	
			4.2	**3.2**	**2.2**	
North Sea	C 90mm	Haddock	20.4	25.1	29.8	Galbraith et al., 1994 (2)
		Whiting	22.8	29.4	36.0	
		Cod	23	28.8	34.7	
			3.5	**Narrow**		
Aegean Sea	C 44mm	Red mullet	13.7	14.3		Lök et al., 1997
		Annular sea bream	9.9	10.1		
			Large	**Standard**		
Adriatic Sea	HC 46mm	Hake	9.7	11.5		Fiorentini and Leonori, 2002
	HC 56mm		12	17.3		
	HC 46mm	Red mullet	6	10.8		
	HC 56mm		9.7	13.4		

(1) All combinations of extension length and cod end diameter have been tested in 80, 90 and 100mm cod ends.
(2) All combinations of cod end diameters have been tested in 90, 100 and 110mm cod ends.

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Table 2 (continued from previous page).
Relationship between L_{50} (in cm) and cod end extension length, cod end diameter and length of lastrige ropes. Cod end mesh sizes are in mm. C - Covered cod end; HC - Hooped covered cod end; TR - trouser trawl; TW - twin trawl.

Area	Experimental conditions	Species		Lastridge ropes		Reference
			Standard	**-15%**		
Barents Sea	TR 135mm	Cod	52.0	58.0		Isaksen and Valdemarsen, 1990
			Standard	**-6%**	**-15%**	
Baltic Sea	C 42mm	Herring	16.9	19.1	18.6	Dahm, 1991
			Standard	**-15%**		
North Sea	TW 135mm	Haddock		-55%		Jacobsen, 1991 (3)
		Cod		-8%		
		Saithe		-10%		
		Red fish		-19%		
			Standard	**-12%**		
Canada	TR 115mm	Deepwater redfish	31.5	33.2		Hickey et al., 1995
	TR 105mm		26.8	32.1		
	TR 90mm		27.2	26.9		
Aegean Sea	C 44mm		**Standard**	**-15%**		Lök et al., 1997
		Red mullet	13.7	15.1		
		Annular sea bream	9.9	9.8		

(3) Selectivity parameters were not estimated. The figures in Table refer to the reduction in numbers of fish.

2.3 Seasonal variation

The importance of seasonal variation in selectivity was demonstrated in a few studies that relate selectivity to differences in body shape associated to seasonal changes in fish condition or to the effects of seasonal temperature changes on fish activity, thus conditioning escape behaviour. Selectivity for cod and haddock was found to increase with increasing girth associated with better fish condition or with increasing water temperature (Tschernij et al., 1996; Özbilgin, 1998; Özbilgin and Wardle, 2002), suggesting that the ability of fish to pass through cod end meshes does not entirely depend on the geometric relationship between fish body and mesh shape, being also affected by fish swimming activity.

2.4 Vessel and sea state related factors

Effects on cod end selectivity of vessel-related factors such as vessel size, vessel-gear interaction (relationship between vessel propulsion and gear drag) and hauling technique were estimated by Tchernij and Holst (1999) for the Baltic Sea cod fishery in seven trawlers using identical cod ends. Hauling type in particular was found to affect L_{50} and SR, with increased selectivity in vessels where haul-back is interrupted, which indicates post-towing escape during this process. Differences in cod end selectivity were also reported for sole (De Clerck et al., 1981); *Nephrops* (Polet and Redant, 1994); and brown shrimp *Crangon crangon* (Polet, 2000), which were related to differences in sea state. These authors refer that sea roughness and the resulting increase in gear motion can promote wash-out effects in the cod end during haul-back, thereby increasing post-towing escape.

In a more recent study, O'Neill et al. (2003) systematically investigated the relationship between sea state induced vessel motion and cod end selection for haddock and whiting. Cod ends were observed to pulse with the frequency of the vessel motion in rough weather, producing changes in mesh slackness that are likely to be responsible for the increase in cod end selectivity during hauls.

2.5 Cod end catch

While the effects on cod end selectivity of most of the above variables were systematically investigated with the purpose of improving the understanding of the selection process in cod ends, other variables, such as haul duration or cod end catch size, were incidentally observed to be related with selectivity in a considerable number of studies. Cod end catch size has been found to affect cod end geometry and reduce the degree of mesh opening in the central part of the cod end, thus conditioning the escape through cod end meshes (Robertson and Stewart, 1988). There is evidence of negative correlation between cod end catch size and selectivity parameters L_{50} or SF, mostly in standard diamond cod ends or cod ends equipped with square mesh windows, in a number of studies e.g. for haddock, cod, whiting, herring, walleye pollack (*Theragra chalcogramma*) and the Argentine hake (*Merluccius hubbsi*) (Table 3). On the other hand, evidence of positive correlation between cod end catch size and selectivity was found for the Norway lobster, haddock, whiting, cod, blue whiting, silver hake (*Merluccius bilinearis*) and for the European hake. A possible explanation for this apparent contradiction can be proposed when the range of cod end catch is taken into account for the different studies (Table 3), suggesting that negative effects of this variable on selectivity tend to be associated with higher catches, while positive effects were generally recorded in studies where lower catch values are reported. O'Neill and Kynoch (1996) suggest a non-linear relationship between cod end catch and selectivity parameters on the basis of cod end mechanical behaviour: as the catch builds up the meshes in front of the cod end open wider and selectivity increases, up to a point where maximum mesh opening is achieved. For higher catches, these authors suggest that the adverse effects on selectivity attributed to mesh closeness in the central part of the cod end, thus reducing the escape area, can possibly be confounded with masking effects resulting from the use of covers. However, this hypothesis is not in accordance with Isaksen et al. (1990) and Suuronen et al. (1991), who reported decreasing L_{50} with increasing catch, in selectivity experiments where trouser trawls were used, while Erickson et al. (1996) report the same effect in alternate hauls experiments. More recently, Madsen and Holst (2002), using covered cod ends equipped with a kite cover, for which no masking effects were observed (see Madsen et al. 2001), have also reported negative effects of cod end catch on L_{50} for cod in catches of up to 700 Kg, while Madsen et al. (2002) using the same cover, found similar effects for cod in catches under 400 Kg, after which L_{50} was observed to stabilise.

Initial increase in selectivity followed by further decrease is probably the most likely mechanism to explain the variability observed for roundfish. However, this mechanism does not apply to flatfish cod end selectivity data (Van Beek et al., 1983), where negative correlation between cod end catch size and SF are reported, at lower catch levels, for sole and plaice (*Pleuronectes platessa*). For such species these effects are likely to be related to cod end mesh clogging by accumulating catches. Polet (2000), in a cod end selectivity study for brown shrimp, where by-catch includes flatfish species, also reported negative correlation between total catch size (or mesh clogging) and L_{50}.

2.6 Haul duration and towing speed

Haul duration, together with towing speed, were found to affect the catching efficiency in trawls by possibly contributing to act as a species and/or a size selecting mechanism (Wardle, 1986, 1987, 1989; He, 1993). While fish swimming in the path of a trawl during the first stages of the catch process tend to keep a constant position relative to the net panels as a result of compensatory movements in response to shifts in their visual field, at a latter stage they can either become exhausted, falling back towards the cod end, or outswim the trawl, depending on whether the trawling speed and/or haul duration exceed fish swimming abilities. This is a complex process affecting catch composition and catch size distribution, and the extent to which it affects selectivity is difficult to predict. Consistent effects of towing speed have not been reported in selectivity studies, even when they have been directly addressed as was the case in experiments by Dahm et al. (2002), for cod and haddock. This is not surprising if the narrow towing speed ranges practiced for a given fishery are taken into account, along with the inherent difficulty of investigating a parameter such as speed. On the other

Table 3.
Relationships between selectivity and cod end catch size. Cod end mesh sizes are in mm. C - Covered cod end; HC - Hooped covered cod end; TR - Trouser trawl; A - Alternate hauls. S refers to square mesh.

Area	Experimental conditions	Species	Cod end catch size (Kg)	Relationship between selectivity and cod end catch size	Reference
Celtic Sea	C 45-75mm	*Nephrops*	30 - 110	positive (on SF)	Charuau, 1978 (1)
Celtic Sea	C 50-75mm	*Nephrops*	0 - 148	positive (on SF)	Charuau, 1979 (1)
South Portugal	HC 55-70mm D, 55mm S	*Nephrops*	0 - 250	positive (on SR)	Paper I
North Sea	C 22mm	Brown shrimp	not specified	negative (on L_{50})	Polet (2000) (2)
Canada	C 60-70mm	Silver hake	0 - 2000	positive (on SF)	Clay, 1979
Argentina	C 110-125mm	Argentine hake	500 - 3000	negative (on SF)	Dahm, 1980
Argentina	C 120mm with and without 90mm window	Argentine hake	720 - 26000	negative (on L_{50})	Ehrhardt, 1996 (3)
SW Portugal	C 65 and 70mm	Hake	100 - 300	positive (on L_{50})	Paper IV
Barents Sea	TR 140mm	Cod and Haddock	100 - 1500	negative (on L_{50})	Isaksen et al., 1990
Baltic Sea	C 120 and 140mm	Cod	500 - 1400	negative (on L_{50})	Tschernij et al., 1996
Baltic Sea	HC 105mm with 115mm square mesh window	Cod	300 - 800	negative (on L_{50}), positive (on SR)	Madsen et al., 1998
Baltic Sea	C 120mm	Cod	8200 - 27500	negative (on L_{50}), positive (on SR)	Tschernij and Holst, 1999
Baltic Sea	C (kite cover) 105mm with 110mm window	Cod	0 - 700	negative (on L_{50})	Madsen and Holst, 2002
Baltic Sea	C (kite cover) 105-140mm	Cod	100 – 1100	negative (on L_{50}) under 400Kg, stabilizing at higher catches	Madsen et al., 2002
Norway	C 100mm	Cod and Haddock	90 - 770	positive (on L_{50})	Dahm et al., 2002
Scottish Sea	HC 100mm	Haddock and Whiting	100 - 400	positive (on L_{50})	O'Neill and Kynoch, 1996
North-Sea	HC 70mm with 90mm square mesh window	Whiting	200 - 1000	negative (on L_{50} and SR)	Madsen et al., 1999
Baltic Sea	C 42mm S	Herring	0 - 1800	negative (on L_{50})	Dahm, 1991
Gulf of Finland	TR 32mm	Herring	200 - 1600	negative (on L_{50})	Suuronen et al., 1991
Bering Sea	A 88 and 113mm, 95 and 108mm S	Walleye pollock	0 - 80 000	negative (on L_{50})	Erickson et al., 1996
South Portugal	HC 55, 60 and 70mm	Blue whiting	50 - 350	positive (on L_{50})	Paper II
SW Portugal	C 65 and 70mm	Blue whiting	50 - 300	positive (on L_{50})	Paper IV
The Netherlands	C 42 mm	Sole and Plaice	0 - 300	negative (on SF)	Van Beek et al., 1983

(1) The influence of the amount of by-catch was reported on SF
(2) The influence of total catch size was reported on L_{50}
(3) The influence of total catch size on L_{50} has been directly addressed

hand, in what regards to the possible effects of haul duration on selectivity, this variable is usually positively correlated to cod end catch, and their separate effects are therefore difficult to analyse.

2.7 Towing depth

The effects of depth on fish escapement from cod ends or other trawl areas have usually been related to the intensity of visual stimuli produced by net panels and rigging at different light levels (Glass and Wardle, 1989; Walsh and Hickey, 1993). However, depth can affect species and size composition of the populations fished, and this can influence selectivity to a considerable extent. In Papers I and II L_{50} and SR were found to increase with increasing depth for blue whiting and rose shrimp respectively, captured in crustacean fishing grounds from 150 to 700 m off the south coast, where larger individuals were captured at greater depths. While for the rose shrimp the observed increase in SR can to a certain extent reflect the wider length intervals recorded at greater depths from 200 to 400 m, the results for blue whiting suggest that the ability of fish to pass through cod end meshes can be affected by variables other than fish dimensions. More active behaviour of bigger fish associated to higher swimming capacity can possibly contribute to explain the unexpected effects of depth on the selectivity for this species.

3. Improving the selectivity in trawl areas external to cod ends

While changing cod end characteristics may lead to more size-selective trawls, allowing for the escapement of undersized fish, the problem of species-selectivity remains unsolved in many fisheries, particularly those where a large number of species are captured as by-catch. In the last two decades, there has been a widespread concern about the level of by-catch and discards associated with multi-species fisheries, and consequently an intensification of the search for alternatives to mesh size regulations. In a global assessment of by-catch and discards, Alverson et al. (1994), estimated the total annual discards in world's marine fisheries to be around 27 million tonnes of fish and other organisms, mostly dead or dying, for a target catch of 77 million tonnes. Discards to landed target catch weight ratios were found to be particularly high for trawl fisheries, especially in shrimp trawling, for which discards were estimated to be 9.5 million tons.

The problem of discards has been addressed in a number of countries through the introduction of physical modifications to conventional trawls. The recognition that trawl selectivity can be manipulated in trawl areas external to the cod end by changing gear design in order to separate and/or exclude species during the catch process, was the key factor when searching for alternatives to mesh size regulations. Crustacean trawling in particular offers a wide basis for gear modifications, since differences in behaviour between crustacean and fish by-catch species can be explored, together with differences in size, in order to reduce by-catch and discards while maintaining the catches of commercial crustaceans.

3.1 Mesh panels

Many different types of modifications to crustacean trawls were tested worldwide over the last decades (for a general review, see Broadhurst, 2000) that include mechanisms based on differences in behaviour between shrimp and fish species, or mechanical sorting by size. In many cases they proved to be successful as by-catch separators or excluders, and some were commercially enforced or have been used on a voluntary basis. In North-Atlantic prawn-trawl fisheries, the utility of a number of different sorting devices, including separator panels and excluding devices, has been examined since the 1960's, with the testing of the first selective trawl equipped with an oblique sorting panel extending from the net mouth until the cod end entrance (Kurc et al., 1965). A number of experiments were carried out in *Nephrops* fisheries using modifications of this panel (Kurc and Betus, 1969) or horizontal panels designed to create two levels inside the trawl connected to two cod ends of different mesh sizes (Symonds and Simpson, 1971; Hillis, 1983, 1985; Ashcroft, 1984; Charuau, 1985; Hillis and Carrol, 1988; Main and Sangster, 1982a, 1982b, 1985a, 1985b). Good results have been reported for a number of designs (Table 4) in the separation between *Nephrops* which, similarly to most benthic invertebrates, has low swimming capacity

Table 4.
Effects of using separator panels on target catch and by-catch reported by different authors. H - horizontal panels. H1- dividing the whole trawl from footrope to cod end. H2 - dividing the rear half of the trawl; H3 - dividing the cod end. O1 - oblique panels in the rear part of the trawl; O2 - oblique panels before the cod end; O3 - HH oblique panels. Panel mesh sizes are in mm.

Area	Separator panels	% separated to upper cod end		Reference
		Target catch	By-catch	
French coast	O1 40mm	*Nephrops*: 2-17%	Hake: 73%	Kurc and Betus, 1969
Irish Sea	H3 50mm	*Nephrops*: 21%	Whiting: 66% ≥ MLS	Symonds and Simpson, 1971
Irish Sea	O1 150mm	*Nephrops*: 12%	Whiting: 86%	Hillis, 1983
Irish Sea	H1 60mm, 0.50m above footrope	*Nephrops*: 0%	Whiting: 96%	Ashcroft, 1984
Irish Sea	H2, 0.75m above footrope	*Nephrops*: 7% ≥ MLS	*Nephrops*: 10% <MLS Whiting: 96% ≥ MLS 86% <MLS	Hillis, 1985 (1)
Irish Sea	H2, 0.75m above footrope	*Nephrops*: 13%	Whiting: 75%	Hillis and Carrol, 1988 (1)
Bay of Biscay	H1 50mm, 0.75m above footrope	*Nephrops*: 7%	Hake: 90%	Charuau, 1985
Celtic Sea		*Nephrops*: 9%	Hake: 58%	
Scotland	H1 85mm, 1.06m above footrope	*Nephrops*: 11%	Whiting: 65% Haddock: 36% Cod: 5%	Main and Sangster, 1982a
	H1 85mm, 0.60m above footrope	*Nephrops*: 14%	Whiting: 80% Haddock: 81% Cod: 17%	
	H1 85mm, 0.45m above footrope	*Nephrops*: 17%	Whiting: 75% Haddock: 86% Cod: 46%	
North Sea	H1 50mm, 0.75m above footrope	*Nephrops*: 1%	Haddock: 96% Whiting: 94%	Main and Sangster, 1985a
South Portugal	O2 120mm	*Nephrops*: 1% ≥ MLS Rose shrimp: 12% ≥ MLS	Rose shrimp: 13% <MLS Boarfish: 67 to 77% Blue whiting: 81% Horse mackerel: 51 to 69% ≥ MLS	Paper V

(1) Panel mesh sizes are not specified.

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Table 4 (continued from previous page).
Effects of using separator panels on target catch and by-catch reported by different authors. H - horizontal panels. H1- dividing the whole trawl from footrope to cod end. H2 - dividing the rear half of the trawl; H3 - dividing the cod end. O1 - oblique panels in the rear part of the trawl; O2 - oblique panels before the cod end; O3 - HH oblique panels. Panel mesh sizes are in mm.

Area	Separator panels	% separated to upper cod end		Reference
		Target catch	By-catch	
Barents Sea	O3 60mm	Pink shrimp: 12%	Haddock: 87% Blue whiting: 86% Cod: 87% Norway pout: 37% European Flounder: 63%	Karlsen, 1976 (2)
Barents Sea	O3 60/55mm	Pink shrimp: 5%	Haddock: 95% Cod: 90% European Flounder: 75%	Karlsen and Mathai, 1978 (2)
North Sea	H1 35mm, 1.50m above footrope	Pink shrimp: 28%	Norway pout: 57%	Main and Sangster, 1985b
Barents Sea	O3 60/55mm	Pink shrimp: 13%	Haddock: 47% Blue whiting: 49% Cod: 71% European Flounder: 72%	Larsen, 1986 (2)
North Sea	O2 100mm	Pink shrimp: 0%	not quantified	Sørensen and Yngvesson, 1987
Barents Sea	H1 120mm, 0.75m above footrope	Haddock: 52% Saithe: 87% Cod: 33%		Valdemarsen et al., 1985
Barents Sea	H2 300mm, square mesh	Haddock: 89% Saithe: 72% Cod: 29%		Engås et al., 1988

(2) In trawls equipped with H-H oblique panels there is no upper cod end and the control of the catch fractions retained by the panels is carried out by means of top covers.

and cannot resist water flow inside the trawl (Main and Sangster, 1985c; Newland and Chapman, 1989), tumbling down the net and being directed to the lower cod end, and fish species such as haddock, whiting and saithe, which tend to swim upwards (Main and Sangster, 1981, 1982a, 1982b,1985b), being captured in the upper cod end.

The resistance to their commercial introduction related either to the increase in gear weight and cost or to operational problems was a major factor contributing to the abandonment this type of design in favour of smaller panels, placed in the rear part of the trawl. By this time oblique sorting panels made in square meshes, placed before the cod end and covering the entire trawl vertical section, associated to escape openings, had already been tested in Norway, aiming at the exclusion of cod, haddock, Norway pout *Trisopterus esmarki* and European flounder *Platichthys flesus* from trawls targeting the pink shrimp *Pandalus borealis*. Karlsen (1976) and Karlsen and Mathai (1978) reported a number of experiments using these types of panels, which were commercially adopted in 1985 in response to regulations that limited fish by-catch in pink shrimp fisheries (Larsen, 1986; Karlsen, 1988).

A different concept of oblique separator panel, to be installed at the rear part of the trawl, was developed for a two cod end trawl by Sørensen and Yngvesson (1987) for the Danish fishery for pink shrimp in the northwestern North Sea, where the by-catch includes a large fraction of round fish including Norway pout, cod and haddock, and also of benthic species such as the Norway lobster, monkfish (*Lophius piscatorius*) and several flatfish species. This panel design includes an upward sloping forepart, installed with the purpose of guiding the higher swimming fish to the upper trawl section, followed by an horizontal small mesh rear part separating the trawl in two different compartments ending in a lower and an upper cod end. The large mesh forepart was made in big meshes to allow shrimps to pass through and be retained in the lower cod end. A passage between the lower trawl belly and the leading edge of the panel was provided to allow the Norway lobster, monkfish and flatfish to be directed to the lower cod end.

This design was tested in the Portuguese crustacean fishery off the south coast (Paper V), showing good results in the separation between crustaceans, Norway lobster and rose shrimp, which were captured at the lower cod end, and small pelagic by-catch species such as the boarfish (*Capros aper*) and the blue whiting, guided to the upper trawl section. However, for horse mackerel and hake a clear separation could not be achieved.

3.2 Square mesh windows

The utility of square mesh windows as by-catch reducing devices based on differences in behaviour between crustaceans and fish, has on the other hand been examined more recently, during the last decade. They have been recognized as preferential fish escape zones when placed in the cod ends or other strategically chosen trawl areas, creating visual stimuli that enhance fish escapement (Briggs and Robertson, 1993; Glass et al., 1993) and modifying the water flow inside the trawl (Broadhurst et al., 1999). Square mesh windows have been tested in *Nephrops* fisheries where the by-catch is comprised mainly of haddock and whiting, as well as in haddock and whiting fisheries, and shrimp fisheries (Table 5). Most studies refer to comparative fishing experiments where square mesh window cod ends have been tested against conventional diamond mesh cod ends using twin trawl rigs, while Hillis et al. (1991) used single trawls in parallel hauls experiments, and in Paper VI a single trawl equipped with a top cover was towed.

In more recent experiments (Graham and Kynoch, 2001), the selectivity of conventional diamond mesh cod ends and the same cod ends equipped with windows placed in the top of the cod end and in the extension was estimated for haddock in the North Sea, by testing them against a control cod end in a twin trawl rig, and a higher L_{50} was reported for the cod end with the window placed at top. On the other hand, Madsen et al. (2002) compared the selectivity of a number of conventional cod ends and window cod ends using the cod end covered method in twin trawls for the Baltic cod fishery. Significantly higher L_{50} and lower SR values were reported for window cod ends with the same mesh size as that of standard cod ends.

While the reported escape percentage through square mesh windows is almost always near zero for

Nephrops and relatively small for shrimps, a considerable reduction of the marketable fish by-catch, along with undersized individuals, has been generally observed associated with the use of these sorting devices (Table 5).

3.3 Sorting grid systems

Sorting grid systems, which were originally developed for species separation and further applied to size separation, were first tested in Norway by the end of the 1980's with the aim of excluding cod, haddock, Norway pout and European flounder from trawls targeting the pink shrimp (Isaksen et al., 1992). In the original design, known as the Nordmøre grid, the grid frame was made in bars covering the entire trawl section, allowing the passage of shrimp towards the cod end, while by-catch species are released through a triangular shaped escape hole placed above the grid at the top of the extension piece. A guiding funnel was placed before the grid with the purpose of forcing all the fish and shrimp to enter in contact with the grid, irrespective of the height of their entrance in the trawl.

Nordmøre grids along with variations of the original design were intensively tested during the last decade in pink shrimp fisheries in Norway (Valdemarsen, 1996), the North Sea (Valdemarsen, 1996; Madsen and Hansen, 2001), off the Canadian East coast (Brothers and Boulos, 1996; Brothers, 1998), as well as in Greenland, Iceland, Spitzbergen and the Barents Sea (Anon, 1996; Anon, 1998). Their evaluation as by-catch excluders was extended to *Nephrops* (Valdemarsen et al., 1996), silver hake and cod (Brothers, 1998), monkfish (Meillat et al., 1994), brown shrimp (Wienbeck, 1997; Polet, 2002) and crustacean fisheries (Fonseca et al., 2001, unpublished data); to Australian shrimp fisheries (Broadhurst et al., 1996); and to the Argentine hake fishery (Ercoli et al., 1997, 1998). Changes to the original design included modifications in the shape or position of the grid frames and in the grid angle of attack; introduction of bottom or top escape passages through which target species larger in size that cannot pass through the grid can be directed to the trawl cod end; and differences in the distance between grid bars, which was adapted to the dimensions of the target species.

In Table 6 some of the results are presented from different studies where Nordmøre-type grid sorting systems have been tested. For a number of them, selectivity parameters could be estimated for the main species. However, unlike for square mesh windows, in most experiments with grids no direct comparisons were made between the selectivity in standard trawls and trawls equipped with grids. Therefore, selectivity parameters are not presented; instead the reported effects on target catch or reduction of by-catch (estimated through the use of top covers attached to the grid escape holes) are shown, when available. Comparative fishing experiments of trawls equipped with grid sorting systems against conventional trawls were carried out by Broadhurst et al. (1996) and Madsen and Hansen (2001), using a twin trawl rig, and by Ercoli et al. (1997) in alternate hauls.

4. Commercial introduction of cod end modifications and species-sorting devices

The improvement of the selectivity in cod ends by using thinner twines and low numbers of meshes in circumference has been widely recognized, and these measures are at present being progressively incorporated in fisheries regulations (see Reg. (CE) 850/98). Some problems are raised, on the other hand, associated to the use of square mesh cod ends. Knot slippage, which can occur with continued use associated to high catches, has been generally reported as a major drawback to their commercial use. Practical problems concerning the use of square mesh cod ends could be successfully overcome with the use of knotless netting (Van Marlen, 1991), but no information was found on the introduction of square mesh cod ends made in knotless netting in fisheries regulations as a way to improve selectivity. However, square mesh cod ends made in conventional netting have been voluntarily used by some fishermen in *Nephrops* trawls in the Skagerrak (Ulmestrand, pers. comm.).

From the vast amount of gear modifications tested in order to reduce by-catch, only a small number has been successfully introduced in the commercial activity. Resistance to their implementation by the final users has been associated to complex designs and high costs, failures in operating efficiently over a range of commercial conditions and undesirable

Table 5.
Effects of using square mesh windows on target catch and by-catch reported by different authors. S1 - windows placed in the top of the cod end; S2 - windows in the top of the cod end extension; S3 - windows in the upper belly. Window mesh sizes are in mm. Experimental method used: TW - twin trawl; P- Paralell hauls; TC - Top window cover.

Area	Square mesh windows	Exp. method	Effects on target catch	Reduction of by-catch	Reference
Irish Sea	S2 75mm in 70mm cod end	TW	*Nephrops*: no effects	72% Whiting <MLS, 42% ≥ MLS	Arkley, 1990
	S2 80mm in 70mm cod end			47% Haddock <MLS	
				63% Whiting <MLS, 55% ≥ MLS	
North sea	S1 90mm in 90mm cod end	TW	Haddock: 20% reduction ≥ MLS	41% Haddock <MLS	Ferro, 1991
			Whiting: 64% reduction ≥ MLS	70% Whiting < MLS	
Irish Sea	S1 70mm in 70mm cod end	P	Whiting: 31% reduction ≥ MLS	41% Whiting, 24% Nephrops <MLS	Hillis et al., 1991
	S1 70mm covering the entire top cod end		49% reduction ≥ MLS	86% Whiting, 40% Nephrops <MLS	
	S3 70mm 7m before cod end		20% increase ≥ MLS	35% Whiting <MLS	
North sea	S1 70mm in 70mm cod end	TW	*Nephrops*: no effects	62% Whiting	Ulmestrand and Larsson, 1991
Irish Sea	S2 75mm in 70mm cod end	TW	*Nephrops*: no effects	15 up to 84% Whiting <MLS	Briggs, 1992
Iceland	S2 80mm	TW	*Nephrops*: no effects	Haddock and whiting: no effects	Thorsteinsson, 1992
	S1 80mm and S3 135mm			42% Haddock, 58% Whiting	
North Sea	S2 80mm in 70mm cod end	TW	*Nephrops*: no effects	no effects	Robertson and Shanks, 1994
	S3 80mm 7m before extension		23% reduction ≥ MLS	65% Haddock <MLS, 26% ≥ MLS	
				91% Whiting <MLS, 90% ≥ MLS	
Irish Sea	S3 75mm 7m before cod end compared to 1m before cod end	TW	*Nephrops* - no effects	34% Whiting <MLS, 48% ≥ MLS	Armstrong et al., 1998 (1)
South Portugal	S3 100mm	TC	Rose shrimp: 24% reduction ≥ MLS	21% Rose shrimp <MLS	Paper V
			Nephrops: no effects	28% Horse mackerel ≥ MLS	
				67% Blue whiting	
				17% Boarfish	
South Portugal	S1 100mm	TC	Rose shrimp: 9% reduction ≥ MLS	9% Rose shrimp <MLS	Paper VI
				54% Blue whiting, 12% Boarfish	
	S3 100mm		Rose shrimp: 11% reduction ≥ MLS	9% Rose shrimp <MLS	
				27% Blue whiting	
North Sea	S2 90mm in 70mm cod end	TW	*Nephrops*: 14% reduction ≥ MLS	50% Haddock <MLS	Madsen et al., 1999 (2)
				33% Cod <MLS	
				59% Whiting ≥ MLS	

(1) By-catch reduction based on the ratio of catch rate (nº/h) with window 7m before extension to catch rate of both windows combined
(2) Selectivity experiment

Table 6.
Effects of the use of grid sorting systems on target catch and by-catch reported by different authors. NT - Nordmore-type grid; NTU - modified grid with upper escape hole; NTL - modified grid with lower escape hole. Distance between grid bars are in mm. TC - top cover; TW - twin trawls; A - alternate hauls.

Area	Sorting grid systems	Exp. method	Effects on target catch	Reduction of by-catch	Reference
Norway	NT, 17-21mm	TC	Pink shrimp: 2-5% reduction ≥ MLS	not reported	Isaksen et al., 1992 (2)
Svalbard	NT, 19 mm	TC	Pink shrimp: 2 to 8% reduction	17 to 48% Cod	Larsen, 1996 (2)
				34 to 84% Redfish	
				80 to 100% Greenland halibut	
				65 to 83% Dab	
				5 to 43% Polar cod	
Australia	NT, 19 mm	TW	King prawn: no effects	77% of by-catch	Broadhurst et al., 1996
Canada	NT, 19 mm	TC	Pink shrimp: 2% reduction	97% of by-catch	Brothers, 1988
Canada	NT, 40 mm	TC	Silver hake: 5% reduction	95% Haddock	Brothers, 1988
				99% Cod	
				96% Pollock	
				38% Herring	
Canada	NT, 127 mm	TC	Plaice: 8% reduction	88% Cod	Brothers, 1988
			Yellowtail flounder: 8% reduction		
Argentina	NTU, 33 mm	A	not reported	Hake: 90% <35cm	Ercoli et al., 1997 (2)
Argentina	NTU, 30 mm	TC	Argentine Hake: 2% reduction ≥ 35cm	34% <35cm	Ercoli et al., 1998 (2)
	33 mm		5% reduction ≥ 35cm	59% <35cm	
	40 mm		33% reduction ≥ 35cm	73% <35cm	
Celtic Sea	NT, 110/65 mm (1)	TC	Monkfish: 9% reduction ≥ MLS	78% <MLS	Meillat et al., 1994
Bay of Biscay			Megrim: 41% reduction ≥ MLS	83% <MLS	
			Rays: no effects	5% <MLS	
			Hake: 28% reduction ≥ MLS	64% <MLS	
South Portugal	NTL, 25mm	TC	Rose shrimp: 4% reduction ≥ MLS	4% reduction <MLS	Fonseca et al., 2001, unpublished
			Nephrops: 5% reduction ≥ MLS	44% Hake ≥ MLS, 25% <MLS	
				50% Conger eel ≥ MLS	
				75% Blue whiting	
				48% Boarfish	

(1) Distance between horizontal and vertical grid bars respectively
(2) Selectivity experiment

Continues on the next page

Table 6 (continued from previous page).
Effects of the use of grid sorting systems on target catch and by-catch reported by different authors. NT - Nordmore-type grid; NTU - modified grid with upper escape hole; NTL - modified grid with lower escape hole. Distance between grid bars are in mm. TC - top cover; TW - twin trawls; A - alternate hauls.

Area	Sorting grid systems	Exp. method	Effects on target catch	Reduction of by-catch	Reference
North Sea	NTU + NTL, 19mm	TW	Pink shrimp: no effects	not reported	Madsen and Hansen, 2001
			Nephrops: 18% reduction ≥ MLS	54% <MLS	
			Haddock: 58% reduction ≥ MLS	88% <MLS	
			Whiting: 88% reduction ≥ MLS	18% <MLS	
			Cod: no effects	69% <MLS	
				39% Norway pout	
North Sea	NT, 12-14mm	TC	Brown shrimp: 13% reduction ≥ MLS	17% reduction <MLS	Polet, 2002 (2)
				70% of fish by-catch	
				65% of benthic species	

(2) Selectivity experiment

effects on gear performance and handling (Broadhurst, 2000). High variability in the separation between cod ends or unavoidable loss of marketable fish for some of the by-catch species has been also reported, mostly for sorting panels and square mesh windows, being likely to be a further reason that can strongly limit their commercial acceptance. However, square mesh windows proved to be successful in a number of fisheries and are now mandatory in Irish and UK *Nephrops* fisheries, as well as in Baltic Sea cod fisheries (Anon, 1996a). Sorting grid systems, on the other hand, were recognized as more efficient devices in species or size-sorting due to their more stable selective properties when compared to flexible devices constructed of netting (Anon, 1996b), and the Nordmøre grid of the type tested by Isaksen et al. (1992) has been mandatory since the beginning of the 90's in the northern shrimp *Pandalus* fisheries, in Norway, Spitzbergen and the Barents Sea (Anon, 1996b), and more recently in Canadian and Icelandic waters (Anon, 1998). Grids have also been commercially introduced in the Argentine shrimp and hake fisheries since 1997 and 2002 respectively (Garcia, pers. comm.). The rigid structure of grids, making them easy devices to describe and inspect, along with the fact that they can be mounted in a separate trawl section, being easy to shift from trawl to trawl, are features that have contributed to their commercial introduction.

Notwithstanding, a modification of the oblique panel concept tested in Paper V has been recently adopted in certain closed areas of the Irish Sea (cod recovery plan – Council Regulation (EC) N° 304/2000) since February 2000. In this version, the panel forepart is associated to an escape opening through which roundfish, including cod, are released from the trawl.

A key factor in the commercial introduction of by-catch reducing devices, is that the benefits perceived by the final users, when adopting these types of devices, overcome the possible loss in terms of marketable by-catch. While economic benefits associated to the increase in quality of target species and reduction of the sorting time on board have been recognized in many fisheries, a major incentive for the development and adoption of BRD's can simply be the access to fishing grounds that otherwise should be closed due to an excessive catch of protected species.

5. Survival of fish escaping from cod ends or modified trawls

A central issue regarding the usefulness and justification of using gear modifications for management purposes is the survival of fish after escaping through cod end meshes or other trawl exit areas. Thus, any studies on the improvement of trawl selectivity should ideally be coupled with the assessment of survival rates. This has been critically examined, particularly during the last decade, in the north Atlantic, where survival has been addressed for a number of species including haddock, whiting, cod, herring and Norway lobster (Table 7). Average survival rates from about 48 up to 97% have been reported for haddock escaping from 70 to 135 mm diamond mesh cod ends (Main and Sangster, 1991; Soldal et al., 1993; Sangster et al., 1996; Wileman et al., 1999, in Madsen, 2000), and from 52 to 98% for whiting within the same range of mesh sizes (Main and Sangster, 1991; Jacobsen, 1994; Sangster et al., 1996; Wileman et al., 1999, in Madsen, 2000), while for cod survival approached 100% in trawl cod ends of 120 mm (Main and Sangster, 1991; DeAlteris and Reifsteck, 1993; Suuronen et al., 1996b). Average survival rates were estimated to be much lower for herring captured with lower mesh sizes of 26 to 36 mm (10 and 40% respectively for fish under and above 12 cm respectively) (Suuronen et al., 1996a). For the Norway lobster, Morizur et al. (1982) reported survival rates of 70% when using 45 mm cod ends, while Wileman et al. (1999) in Madsen (2000) point to approximately 80% survival in diamond cod ends between 70 and 100 mm mesh size. Survival rates were found to be higher for haddock and whiting with increased mesh size, with the use of square mesh cod ends or cod ends equipped with windows, and with the use of grids; and for the Norway lobster, with the use of square mesh cod ends. For these species, this is definitely an argument in favour of the introduction of such gear modifications in management programmes.

Table 7.
Survival of different species after escaping through trawl cod ends or by-catch reduction devices (adapted from Madsen, 2000)

Area	Experimental conditions	Survival	Reference
Bay of Biscay	45mm diamond mesh cod ends, 60-78 hours in sea bed cages	*Nephrops*: 70%	Morizur, 1982 (1)
NW Scotland	60mm square mesh cod end, 14 days in sea bed cages	*Nephrops*: 86%	Wileman et al., 1999 (2)
	70mm cod end, 11 days in sea bed cages	*Nephrops*: 81%	
	100mm cod end, 14 days in sea bed cages	*Nephrops*: 79%	
NW Scotland	90mm diamond mesh cod ends, several weeks in sea bed cages	Haddock: 60-86%; Whiting: 83-97%; Cod: 91-100%	Main and Sangster, 1991
	100mm diamond mesh cod ends, several weeks in sea bed cages	Haddock: 83-97%	
	80mm square mesh cod ends, several weeks in sea bed cages	Haddock: 86-97%	
	80mm square mesh window cod ends, several weeks in sea bed cages	Haddock: 72-82%; Whiting: 88-100%; Cod: 100%	
Barents Sea	135mm diamond mesh cod end, 9-16 days in sea bed cages	Haddock: 96%	Soldal et al., 1993
	Grid sorting system, 13-14 days in sea bed cages	Haddock: 92%	
NW Scotland	70mm diamond mesh cod end, 60 days in sea bed cages	Haddock: 48-67%; Whiting: 52-60%	Sangster et al., 1996 (1)
	90mm diamond mesh cod end, 60 days in sea bed cages	Haddock: 79-82%; Whiting: 73-78%	
	100mm diamond mesh cod end, 60 days in sea bed cages	Haddock: 73-83%; Whiting: 67-77%	
	110mm diamond mesh cod end, 60 days in sea bed cages	Haddock: 85-89%; Whiting: 83-86%	
Barents Sea	Nordmøre shrimp grid, 5-6 days in sea bed cages	Haddock, Whiting and Cod: 100%	Soldal and Engås, 1997
NW Scotland	70mm cod end, 23-25 days in sea bed cages	Haddock: 80%; Whiting: 98%	Wileman et al., 1999 (2)
	100mm cod end, 23-25 days in sea bed cages	Haddock: 86%; Whiting: 92%	
	100mm cod end, 1 hour towing, 8-10 days in sea bed cages	Haddock: 94%; Whiting: 97%	
	100mm cod end, 3 hours towing, 8-10 days in sea bed cages	Haddock: 96%; Whiting: 98%	
West Atlantic	120mm diamond and square mesh cod ends, 10 days in sea bed cages	Cod: 100%	DeAlteris and Reifsteck, 1993
Baltic Sea	95mm PA square mesh window cod end, 13 days in sea bed cages	Cod: 98%	Suuronen et al., 1996b
	95mm knotless UC square mesh window cod end, 12-14 days in sea bed cages	Cod: 100%	
	Open cod end extension, 11days in sea bed cages	Cod: 100%	
Baltic Sea	26/36mm pelagic cod ends, 1.5-9 days in floating cages	Herring < 12 cm: 9%; Herring 12-17 cm: 38%	Suuronen et al., 1996a (3)
	Open cod end extension, 1.5-9 days in floating cages	Herring < 12 cm: 9%; Herring 12-17 cm: 38%	

(1) Higher survival is reported with increase in length
(2) Data in Madsen, 2000
(3) Predicted 14 day post-capture survival

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Overview of the thesis

Aida Campos

IPIMAR, Portuguese Institute for Fisheries and Sea Research, Avenida de Brasília, 1449-006, Lisbon, Portugal

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1. Introduction

1.1. Fisheries regulations and state of stocks

The Portuguese continental shelf (ICES Sub-area IXa) has been subject to intense exploitation by the bottom trawling fleet targeting fish species. This activity extends, particularly off the south coast, to vast areas of the slope, where crustaceans are targeted by another segment of the bottom trawling fleet, the crustacean trawlers. Both fleets capture a large number of species, using cod end mesh sizes of 65 and 55 mm respectively.

Regulations have been traditionally based on a TAC system for fish species such as the European hake, *Merluccius merluccius*, the horse mackerel, *Trachurus trachurus*, and more recently, the megrims (*Lepidorhombus boscii* and *Lepidorhombus whiffiagonis*), and the monkfishes (*Lophius budegassa* and *Lophius piscatorius*). Among the crustaceans only the Norway lobster *Nephrops norvegicus* is subject to a TAC.

Technical measures such as minimum landing sizes, minimum cod end mesh sizes and limits for the relative percentages of target and by-catch species are applied to both fisheries. While a seasonal closure has been implemented in the south-west coast to protect juvenile hake, there has been considerable resistance to the increase in current cod end mesh sizes proposed by EC Regulations. Until 2000, cod end mesh sizes have been fixed at 55 mm for the crustacean trawl fishery, and a lower limit of 30% of crustaceans in the total landings weight has been imposed, together with upper limits for by-catch protected species (subject to a minimum landing size) between 50 and 60%. The enforcement of these by-catch limits has been a main reason for discarding or misreporting of commercial by-catch. For fish trawling the cod end mesh size has been 65 mm, and an upper limit of 5% in weight of non-target species (crustaceans) allowed.

For most stocks exploited in this area, landings have been decreasing since the beginning of the 1980's (ex: hake) or the 1990's (megrims, monkfish), while a general decrease has also been observed in the spawning stock biomass and recruitment for hake and megrims. These stocks have been considered to be outside the safe biological limits by the ICES Advisory Committee on Fishery Management (Anon, 2001). For *Nephrops*, a sharp decrease in landings has been reported since 1992, along with a decrease in stock biomass and recruitment. According to the Working Group on *Nephrops* stocks (Anon., 1999), recruitment failure is believed to be one of the main reasons for the rapid decline in this stock. As a consequence of the Norway lobster decline, there was a shift of target species to the rose shrimp *Parapenaeus longirostris* and landings for this species have increased since 1992 attaining the maximum value ever observed (2081 t) in 1999. Several years of good recruitment are referred to as having contributed to maintain this situation (Anon, 1999). However, Mattos e Silva, (1995) already presented evidence of overexploitation of the rose shrimp stock. Since 1999, landings have decreased to much lower levels. In 2002, only 480 t were landed (C. Silva, pers. comm.).

Increases in the minimum cod end mesh sizes from 55 to 70 mm in crustacean trawling, and from 65 to 80 mm in fish trawling, were proposed in 1991 for zone 3 (EC) to become effective in January 1995 if no evidence of stocks recovery was observed. The use of more selective gears has also been proposed within the ICES Working Group on *Nephrops* stocks in successive meetings. These recommendations were never adopted, since it has been commonly argued that the multispecies nature of bottom trawl fisheries does not comply with specific technical measures aiming at the protection of only one or a restricted group of target species.

Reg. (EC) 850/98, which has become effective since January 2000, introduced some changes to technical measures, 70 mm being the minimum mesh size allowed for *Nephrops* and hake. However, some practical problems in the enforcement of these measures have to be considered taking into account that, in Portuguese waters there is no evidence, either for *Nephrops* or hake, that these species are separately targeted in bottom trawl fisheries.

1.2. Discards

Recent studies have shown that discards can attain very high levels in Portuguese fisheries. Borges et al. (2001), in the first assessment of discards carried out for a number of *métiers* off the coast of Algarve (south Portugal), report discard levels of 62 and 70% of the mean catch per trip, from 1996 to 1997, in fish and crustacean trawl *métiers* respectively (Table 1), these figures being within the range of those presented by Alverson et al. (1994) for sub-tropical areas. Comparison of these data with more recent estimates (Borges et al., 2000, 2002; Monteiro et al., 2001) show some differences both in discard rates and main discard species (Table 1). However, in three out of four studies carried out for crustacean trawling, the blue whiting, *Micromesistius poutassou*, was found to be the main discard species, ranging from 24 to 48% of the total discarded weight, while in fish trawling the snipefish, *Macroramphosus* sp., was the main discard (11 and 38%) in two out of three studies carried out. Temporal variability in the abundance of these small schooling species is pointed out as the major factor determining the species composition and relative importance of discards (Monteiro et al., 2001).

1.3. Scope of the study

The improvement of size-selectivity by increasing cod end mesh size and changing mesh configuration was evaluated for the deep groundfish assemblage off the south coast exploited by crustacean trawlers (Papers I and II), and in the shallow and deep groundfish assemblages off the south west coast, where a number of fish trawlers usually operate (Papers III and IV).

Cod end selectivity parameters of three different mesh sizes and two mesh configurations, diamond and square mesh, were estimated for seven commercially valuable species (Norway lobster, rose shrimp, red shrimp *Aristeus antennatus*, hake, horse mackerel, axillary seabream *Pagellus acarne* and four-spot megrim *Lepidorhombus boscii*) and one species with low commercial value (blue whiting). In a number of cases, the data structure allowed for the analysis of between-haul variation, and selectivity models were proposed which relate the estimated parameters to the variables tested and also to external variables such as cod end catch and trawling depth, providing a first insight into the mechanisms involved in cod end selectivity in Portuguese trawl fisheries.

By-catch reducing devices (BRD's) placed in the rear part of the trawls or in the cod end, comprising three different combinations of oblique separator panels in association with square mesh windows, and a square mesh window alone, were tested in a crustacean trawl off the south coast with the purpose of excluding as high as possible a fraction of the non-commercial by-catch (Paper V) while in a later study square mesh windows placed in two different positions within the trawl were tested with the same purpose (Paper VI). The effectiveness of the different types of BRD's was separately evaluated for the most important species. Differences between species in behaviour towards the sorting devices are discussed. Size-dependence in escapement through the square mesh windows was recorded for a number of species, and occasionally the window selectivity could be estimated.

2. Materials and Methods

2.1. Data analysed

2.1.1. Cod end selectivity data

Cod end selectivity data were collected along two sets of experiments, carried out in 1992 and 1993 on board the R/V "Noruega" from IPIMAR, with a total of 133 and 112 valid hauls respectively for the different cod ends tested (Fig. 1, Table 2).

For fish trawling, the selectivity experiments were carried out off the south-west coast, from Sesimbra, in the north, to Arrifana, in the south. Two surveys were carried out which were distinct in time, the first in May, with most hauls in shallow areas (50 to 100 m) of the continental shelf, and the second in August, covering mostly the upper slope at depths from 200 to 400 m. The experiments for crustacean trawling were in March/April and May 1993, covering the entire south coast from Vila Real de Santo António, in the east, to Sagres, in the west, at depths from 150 to 700 m.

The catches (cod end and cover catches) were separated, weighed, and identified to the species whenever possible. For many cases this was not possible, and in such cases the genus, or only the family, were determined. The species of commercial interest were subject to length sampling, the only exception being the blue whiting, for which the huge catches led us to consider it worthy of analysis.

The species composition in weight, for all hauls, in the cod end and cover is shown in Fig. 2 for both sets

Table 1.
Discard rates (mean weight per trip) in crustacean and fish trawling at the Portuguese south coast. Seasonal variation is in brackets. Only the three most discarded species are shown.

Métier	Time period	Nº trawlers	Nº fishing trips	Nº hauls	Discard rates	Main discard species	Reference
Crustacean trawling	Spring 96/ Spring 97	6	11	30	70% (s.d. 0.23)	Dark electric ray (*Torpedo nobiliana*): 15% Small spotted dogfish (*Scyliorhinus canicula*): 15% Conger eel (*Conger conger*): 10%	Borges et al., 2001
	Spring 98/ Spring 99	5	16	41	43% (34-52%)	Blue whiting (*Micromesistius poutassou*): 24% Broadtail squid (*Illex coindetii*): 9% Blackmouth shark (*Galeus melastomus*): 8%	Borges et al., 2000 (1)
	Summer 98/ Autumn 99	-	-	25	37% (5-76%)	Blue whiting (*Micromesistius poutassou*): 34% Silvery pout (*Gadiculus argenteus*): 10% Mediterranean slimehead (*Hoplostethus mediterraneus*): 8%	Monteiro et al., 2001 (2)
	Summer 99/ Summer 01	6	36	82	65% (33-89%)	Blue whiting (*Micromesistius poutassou*): 48% Scabbardfish (*Lepidopus caudatus*): 6% Boarfish (*Capros aper*): 3%	Borges et al., 2002 (1)
Fish trawling	Summer 96/ Spring 97	3	7	36	62% (s.d. 0.33)	Snipefish (*Macroramphosus* sp.): 38% Chub mackerel (*Scomber japonicus*): 17% Boarfish (*Capros aper*):15%	Borges et al., 2001
	Winter 97/ Spring 99	3	10	51	59% (41-74%)	Chub mackerel (*Scomber japonicus*): 30% Small spotted dogfish (*Scyliorhinus canicula*): 14% Snipefish (*Macroramphosus* sp.): 9%	Borges et al., 2000 (1)
	Summer 99/ Summer 01	3	36	82	41% (27-75%)	Snipefish (*Macroramphosus* sp.): 11% Mackerel (*Scomber scombrus*): 8% Bogue (*Boops boops*): 8%	Borges et al., 2002 (1)

(1) refers to values estimated from plots.
(2) discard rates were calculated as discards biomass/ discards + commercial crustaceans. The biomass comprising landed by-catch was not taken into consideration.

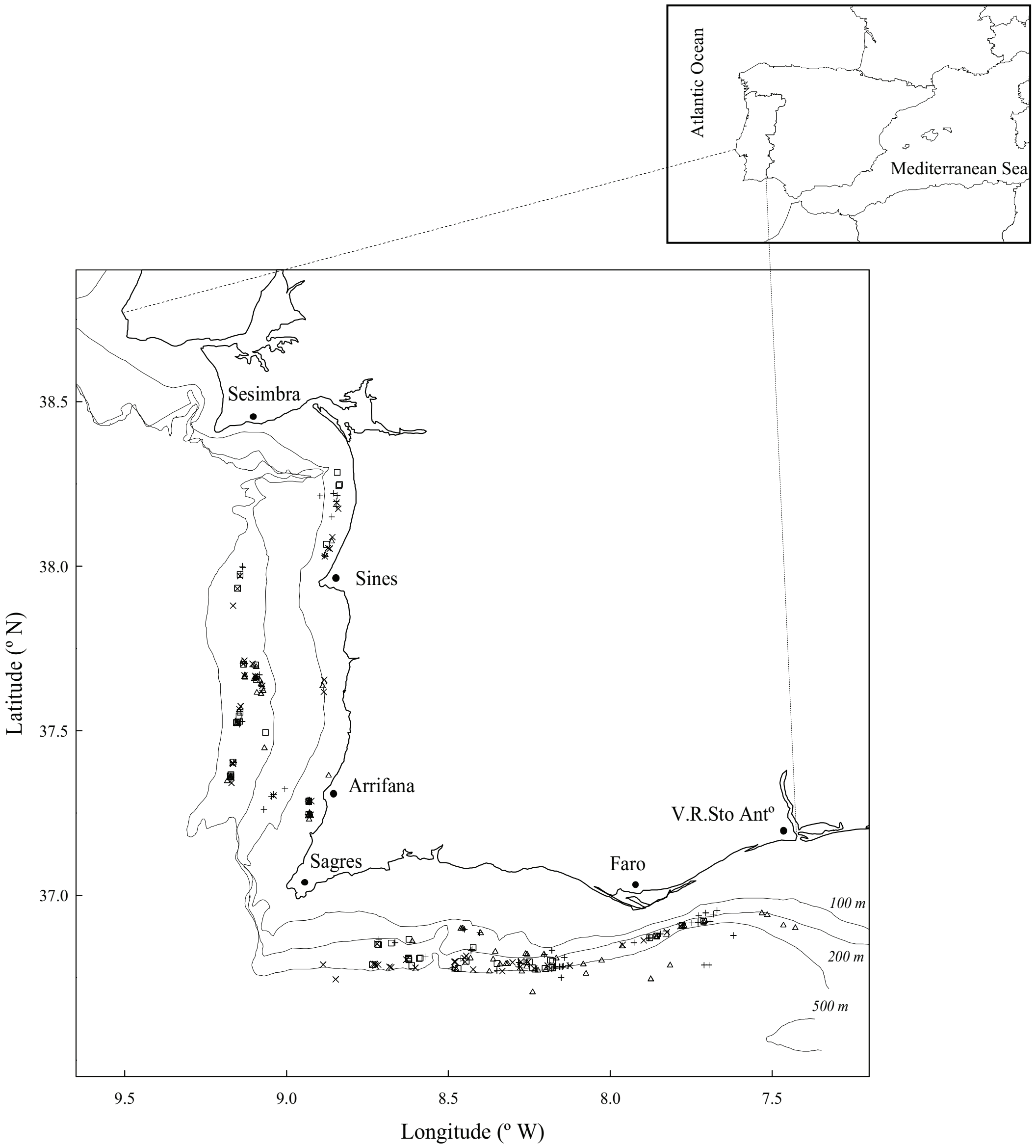


Fig. 1. Cod end selectivity hauls in fish (south-west coast) and crustacean trawling (south coast). Fish surveys 65 mm (+); 70mm (△); 80mm (×); 65 mm square mesh (□). Crustacean surveys 55 mm (+); 60mm (△); 70mm (×); 55 mm square mesh (□).

Table 2
Cod end selectivity experiments. D: diamond mesh; S: square mesh.

Fish trawling - South-west coast (May/August 1992)		Crustacean trawling - South coast (March/May 1993)	
Mesh sizes	Nº hauls	Mesh sizes	Nº hauls
55D	41	65D	25
60D	33	70D	20
70D	35	80D	33
55S	24	65S	34
Total nº	133		112

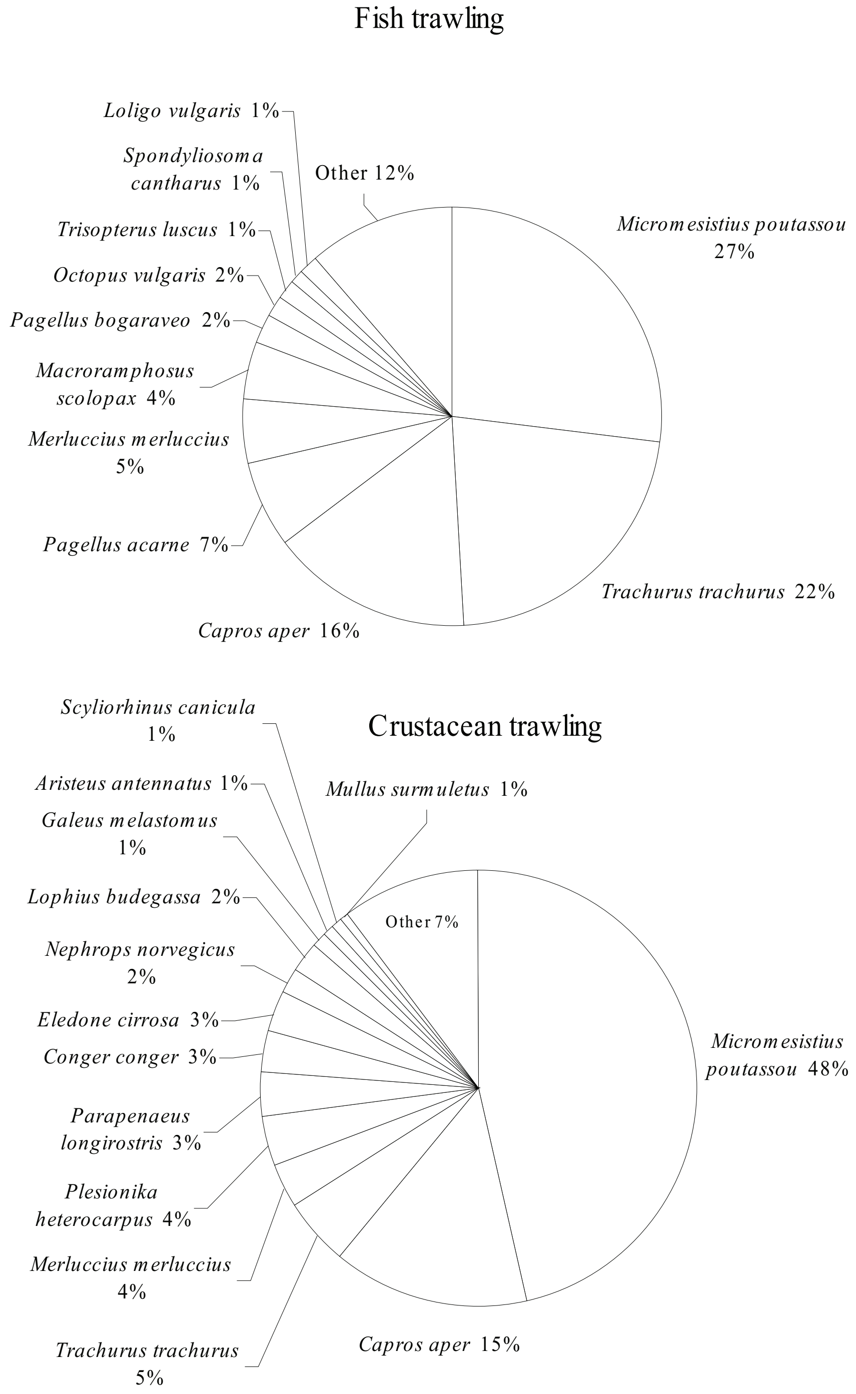


Fig. 2. Species composition by weight in cod end + cover for fish and crustacean trawling. The figures correspond to total catches of 21,660 Kg and 28,283 Kg in 133 and 112 hauls respectively.

of experiments. Off the south-west coast, the catches were dominated by three species, blue whiting, horse mackerel, and boarfish, *Capros aper*, which accounted together for 65% of the total catch biomass. Besides horse mackerel, the most relevant species of commercial interest were the seabreams, the axillary seabream *Pagellus acarne*, the blackspot seabream *Pagellus bogaraveo* and the black seabream *Spondyliosoma cantharus*, accounting together for 10% of the total catch weight, while hake and pout *Trisopterus luscus* accounted for 6%, and the cephalopods *Octopus vulgaris* (common octopus) and *Loligo vulgaris* (European squid) represent together 3% of the total catch. The longspine snipefish *Macroramphosus scolopax* is a non-commercial species captured in high quantities (4% of the total catch) and therefore worthy of reference.

Off the south coast, blue whiting was the dominant species, accounting for 48% of the total catch biomass, followed by the boarfish, with 15%. The horse mackerel and the hake are the main commercial fish species, accounting for 5 and 4% of the catches respectively, whereas shrimps included the arrow shrimp *Plesionika heterocarpus* (4%) the rose shrimp (3%) and the Norway lobster (2%).

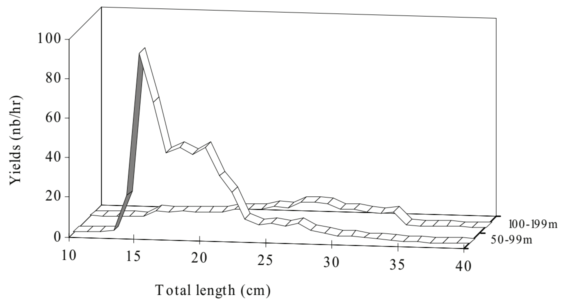
From Figs. 3 and 4, where fishing yields in number of individuals per hour are expressed as a function of length class and depth stratum for the most important sampled species in fish and crustacean trawling, differences can be observed between species in terms of their distribution in depth. However, while off the south coast the depth distributions of crustaceans and by-catch species partially overlap, this was not the case for the experiments carried out off the south-west coast. Here, blue whiting and four-spot megrim were mainly captured in the continental slope (200 to 400 m), while the axillary seabream was always captured in the shelf at depths from 50 to 100 m, and finally hake and horse mackerel were found in a wide depth range from 50 to 400 m.

Length-dependence on depth is clear from Figs. 3 and 4, particularly for those species captured in larger numbers over a wide depth range, such as the rose shrimp and the blue whiting in crustacean trawling, and horse mackerel in fish trawling at the south-west coast, with smaller individuals captured at lower depths.

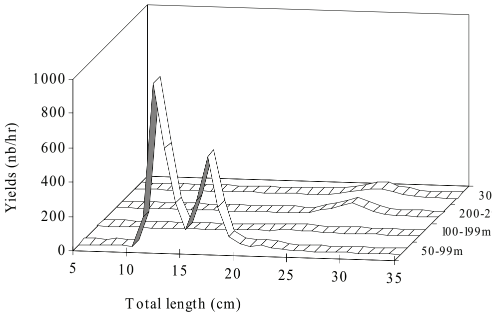
The above spatial patterns are in agreement with the existence of two different groundfish assemblages, characterized by Gomes et al. (2001). A shallow groundfish assemblage is defined by these authors where horse mackerel and the seabreams, mainly the axillary seabream, comprise significant proportions of the biomass inshore, while in deeper waters below the 150 m isobath, the biomass is dominated by blue whiting, with horse mackerel and hake being found to be common species for these two assemblages. However, several studies suggest that both species are found in the two assemblages at distinct stages of their respective life cycles. While juveniles of horse mackerel are mainly concentrated on the continental shelf (Murta and Borges, 1994), the adults can be also found on the shelf until the winter-spring spawning, after which they apparently move to the deeper waters of the upper slope, where they are captured in the summer (Borges and Gordo, 1991; Murta and Borges, 1994). For hake, Cardador (1995) reports the concentration of the lower length classes, including recruits under 17 cm, in deeper waters.

In contrast to the analysis of the selectivity data from the south coast, where the hauls were carried out only in deeper waters below 150 m, the data from the south-west coast were separately analysed for these two distinct assemblages. In Paper III the selectivity was estimated for horse mackerel, hake and axillary seabream, the most abundant commercial species of the shallow fish assemblage, from the hauls carried out to depths of approximately 100 m, while in Paper IV selectivity data are presented for the first two species, together with blue whiting, the dominant species of this assemblage, using the hauls carried out between 200 and 400 m. The effects of seasonal changes in the length distributions of horse mackerel and hake, as well as possible seasonal changes in fish condition, were removed by excluding seasonal variation from the analysis. Therefore, in Paper III only the hauls carried out in the May cruise were considered (a total of 28 hauls), while in Paper IV the selectivity data are only from hauls carried out in August (60 hauls).

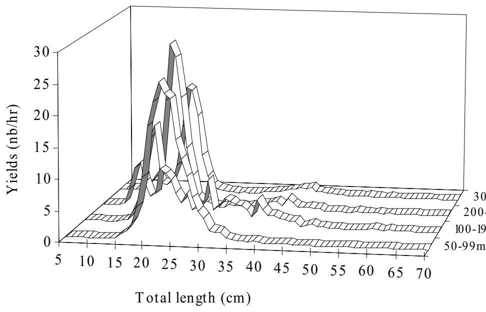
Axillary seabream



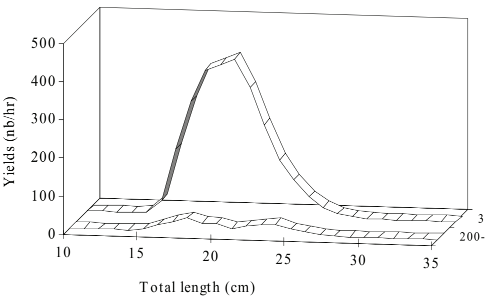
Horse mackerel



European hake



Blue whiting



Four-spot megrim

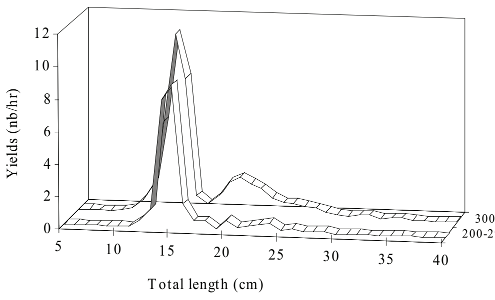


Fig. 3. Fishing yields (in number of individuals per hour) as a function of length class and depth strata for the most captured species off the south-west coast.

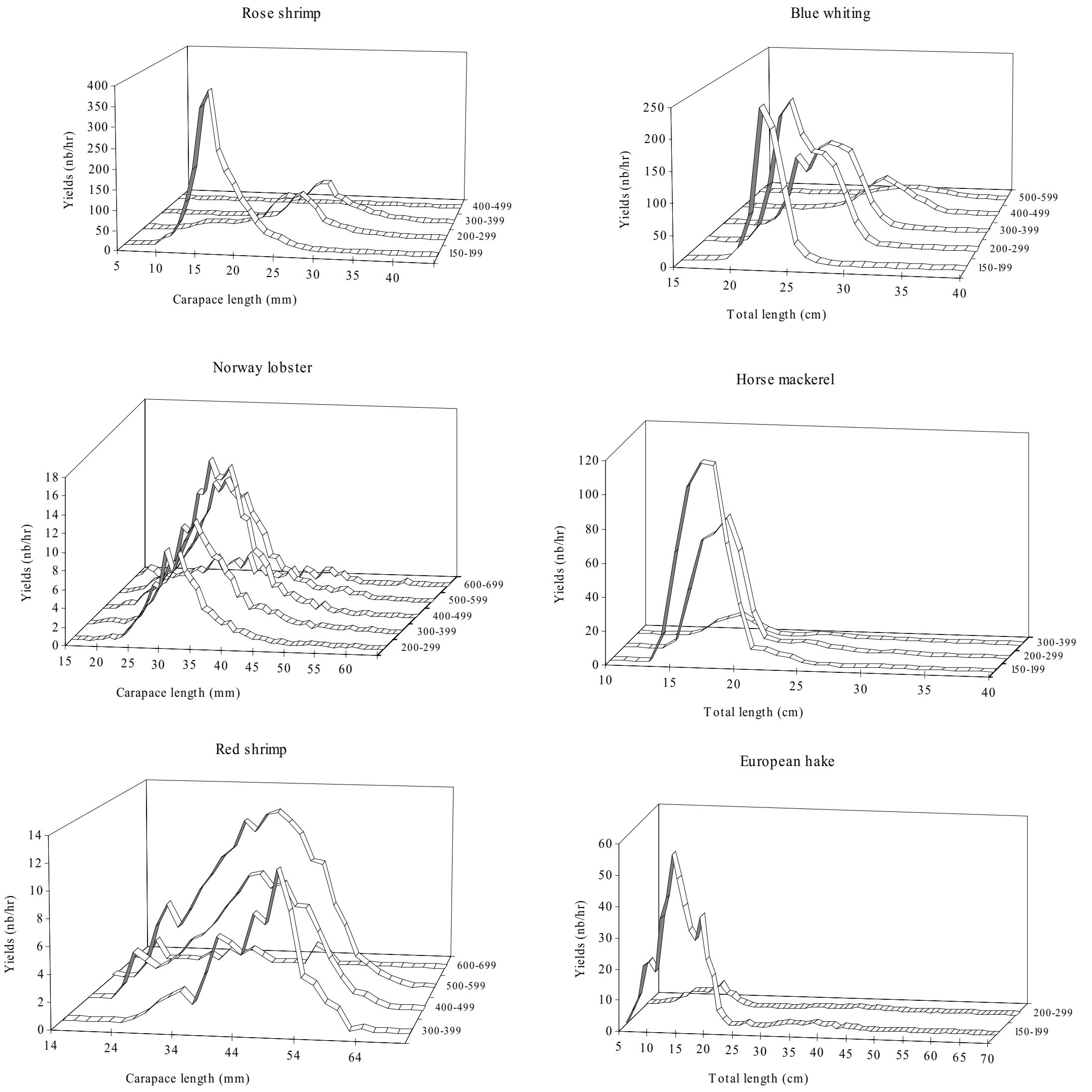


Fig. 4. Fishing yields (in number of individuals per hour) as a function of length class and depth strata for crustaceans and main by-catch species.

2.1.2. Selectivity data from trawls equipped with by-catch reduction devices

These experiments were carried out in crustacean fishing grounds off the south coast (Fig. 5). In the first experiments (July 1993 to May 1994, Paper V), a trawl of commercial design equipped with separator panels and square mesh windows was tested. The data were collected during two sea trials on board the R/V “Mestre Costeiro”, and a short trip on the F/V "Cidade de Tavira". Fishing areas included commercial fishing grounds between Sagres and Faro, at depths from 180 to 500 m, with a total of 26 valid hauls, in which three different combinations of oblique separator panels in association to square mesh windows, and a square mesh window alone, were tested (Table 3).

During the first sea trial, in July 1993, a 120 mm mesh size separator panel and a 70 mm square mesh window were tested, while in the commercial trip (September 1993) the square mesh window was replaced by another with 100 mm mesh size. In May 1994 the mesh size in the separator panel forepart was reduced to 80 mm, while in a second phase the separator panel was removed and the 100 mm mesh size window was tested alone.

Square mesh windows experiments (Paper VI) were carried out in April 1998, on R/V “Noruega”. Altogether, 23 valid hauls were carried out in fishing grounds from Lagos to Tavira, at depths from 200 to 375 m, using the vessel’s demersal trawl.

Windows of 100 mm mesh size were tested placed at two different positions (Table 3). In the first 12 hauls, a 3 m long window was placed in the upper belly 3.3 m before the trawl cod end, while in the next 11 hauls a smaller window (2 m long) was placed on the cod end top panel, 0.5 m after the cod end joining row.

During these experiments, total catch weight was recorded for each cod end (lower, upper and window cover, or lower cod end and cover only), along with the weight of the main target and commercial by-catch species. Carapace length and total length of commercial crustacea and by-catch fish species (including the blue whiting) were measured to the millimetre and centimetre below respectively, with the exception of the hauls on board the F/V "Cidade de Tavira" (Paper V), where the working conditions did not allow for length sampling. In the first experiments the catches were dominated by the boarfish, while blue whiting was the dominant species in the 1998 survey when the square mesh windows were tested (Fig. 6). Norway lobster catches were scarce in this last survey due to the smaller depths prospected.

2.2. Experimental methods

2.2.1. Cod end covers

The control of the individuals escaping through the cod ends was carried out by means of small mesh covers. The covered cod end is the most commonly used experimental method when fishing with a single trawl, as is the case of south European fisheries, and the one that allows for direct estimation of the selectivity since there is the possibility of a direct comparison of the fraction retained with that escaping through the cod end meshes. However, a major drawback associated with this method compared to others such as trouser trawls or twin-trawls is the possible occurrence of a masking effect due to physical contact between cod end and cover, which can be responsible for the increase in cod end retention rates, therefore biasing the results (Pope et al., 1975; Wileman et al., 1996). Besides, the small mesh cover may negatively affect the fish escape process by means of visual effects, or due to effects on fish swimming performance caused by alterations in the water flow.

Minimization of eventual masking effects in cod ends deserved considerable attention of several authors who have tested modified cover designs with larger dimensions and mesh sizes, including square mesh covers (Stewart and Robertson, 1985) or covers of similar design supported by hoops (Robertson and Leaver, 1989; Main and Sangster, 1991; Main et al., 1992; Robertson et al., 1995). The use of these covers is strongly recommended by the ICES manual of methods of measuring the selectivity of towed fishing gears (Wileman et al., 1996). However, cover damage associated to the use of hoops has been reported in experiments where the whole trawl, including the cod end, is in close contact with the bottom, as it is the case of beam trawls (Polet, 1994).

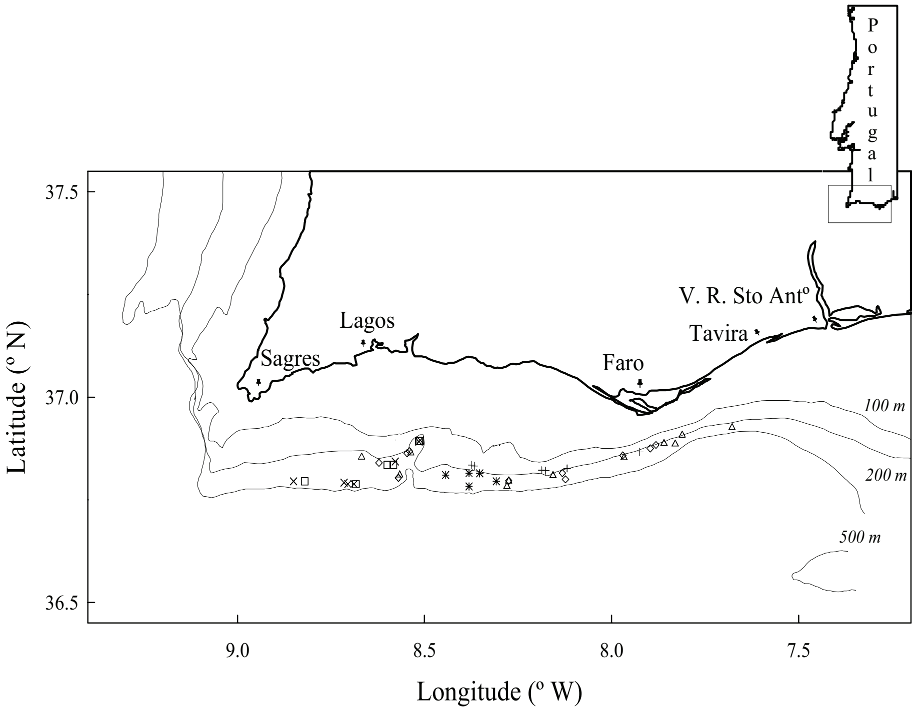


Fig. 5. Hauls carried out with by-catch reduction devices at the south coast. 120 mm sorting panel and 70 mm square mesh window (✳); 120 mm panel and 100 mm window (+); 80 mm panel and 100 mm window (×);100 mm window (□);100mm window at trawl belly (△); 100 mm window at the top of the cod end (◇)

Table 3
Experiments carried out with by-catch reduction devices. SP: separator panel; SMW: square mesh window.

BRD's tested	Vessel	Date	Nº hauls
SP 120mm + SMW 70mm	R/V "Mestre Costeiro"	July 93	6
SP 120mm + SMW 100mm	F/V "Cidade de Tavira"	Sep. 93	6
SP 80mm + SMW 70mm	R/V "Mestre Costeiro"	May 94	7
SMW 100 mm at trawl belly	R/V "Mestre Costeiro"	May 94	7
SMW 100 mm at trawl belly	R/V "Noruega"	April 98	12
SMW 100 mm at cod end	R/V "Noruega"	April 98	11

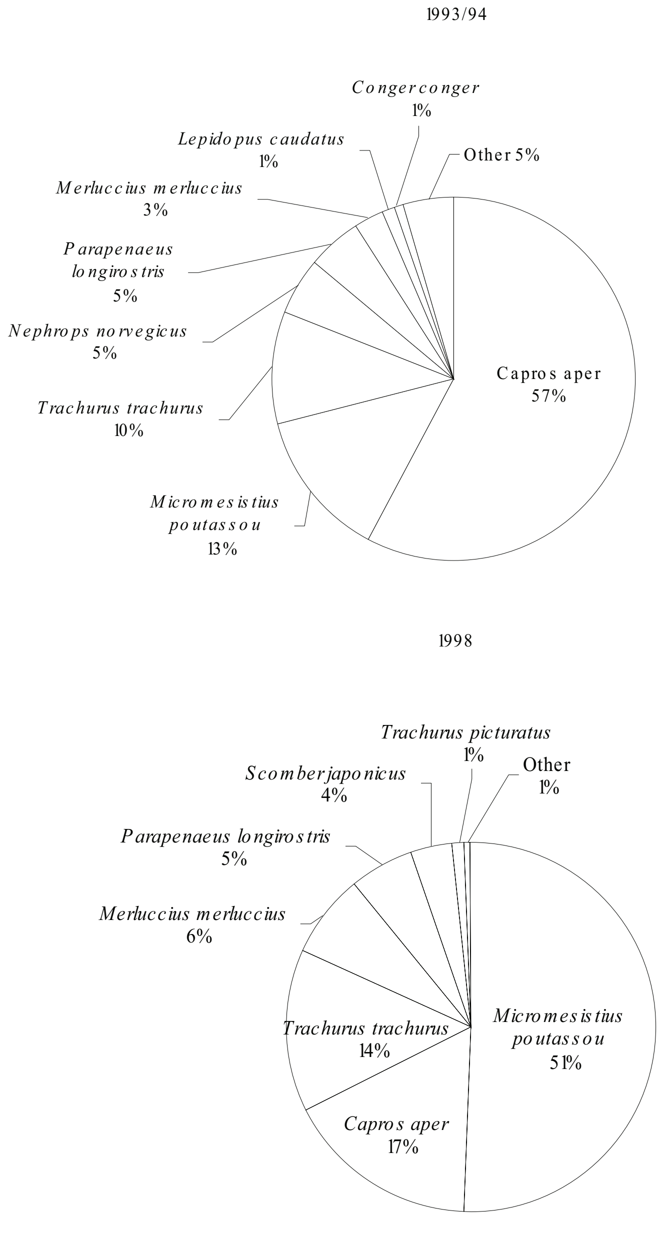


Fig. 6. Species composition by weight in the experiments carried out with by-catch reduction devices. The figures correspond to total catches of 3,154 Kg and 3,854 Kg in 26 and 23 hauls respectively.

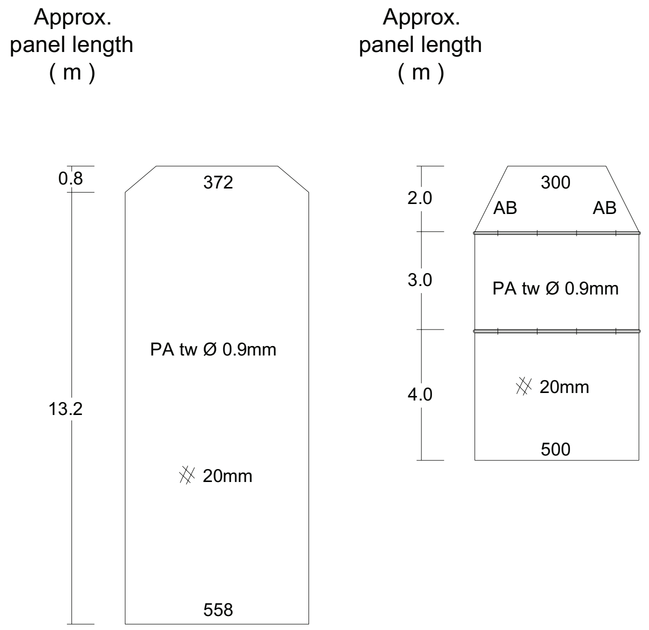
The covers used in our cod end selectivity experiments (Fig. 7) were made in 20 mm mesh size polyamide twine, 1.5 times larger than the length and width of the cod ends, as recommended by Stewart and Robertson (1985). In the first experiments (Paper III; Paper IV) no hoops were used, while in Papers I and II circular hoops of 2.2 m diameter made of galvanized iron were fitted inside the cover. Cover damage in the points of attachment of hoops was recorded during some hauls in these experiments, particularly when higher catches were found at the cover.

Despite the fact that covers are currently used, only one study was found (Polet, 1994) where the cover effect on selectivity was estimated by means of direct comparison between covered and uncovered cod ends. This author compared the selectivity of a cod end surrounded by a 40 mm hooped cover with that of a similar uncovered cod end for sole, *Solea solea*, and dab, *Limanda limanda*, in a twin beam trawl rig, and found SF estimates 12 to 15% higher for the cod end without cover. It would be of interest to test for possible effects on selectivity of small-mesh covers as the one used in the present experiments.

On the other hand, the influence of cover mesh size on cod end selectivity was estimated by O'Neill and Kynoch (1996) for 40 and 60 mm hooped covers in a twin-trawl, and no significant effects on L_{50} and SR were found for whiting, *Merlangius merlangus*, and haddock, *Melanogrammus aeglefinus*.

Recently, a new type of cover was proposed by Madsen et al. (2001), which is kept away from the cod end by the use of kites attached to the cover top and sides, and chain attached to the bottom, in order to generate spreading forces. The effects on selectivity of using this cover, made of 50 mm mesh size, were assessed by directly comparing the selectivity of a covered window cod end with that of a similar uncovered cod end, in a twin trawl rig for the Baltic Sea cod (*Gadus morhua*) fishery (Madsen and Holst, 2002). No significant cover effects were found in L_{50} or SR, which makes the use of a cover of this type a possible option in cod end selectivity experiments.

Regardless of the type of cover used, in cod end selectivity experiments what is actually being estimated is the cod end selectivity and not the overall trawl selectivity. While escapement is usually assumed to occur through cod end meshes, escapement through other trawl areas, including the wings, bellies and cod



a) b)

Fig. 7. Cover designs in cod end selectivity experiments: a) in fish trawl; b) in crustacean trawl. The points of attachement of hoops are shown in b).

end extensions, or under the footrope, may also be significant, and has been long reported for bottom trawls (Margetts, 1963; Briggs, 1986; Engås and Godø, 1989; Dremière et al., 1999). In the case of the crustacean trawl used in Papers I and II, it can be assumed that cod end selectivity does not differ much from the whole trawl selectivity given the small mesh size used in the trawl wings and bellies, which is similar to the cod end mesh size. On the other hand, the larger mesh sizes used in the wings and bellies of the trawl tested in Papers III and IV, may have allowed for some escapement within these trawl areas. Differences between the trawls used in these experiments were pointed out as a possible reason for differences in the selectivity estimates for the same species when captured in cod ends of similar mesh size (Paper IV).

2.2.2. Window covers

The control of the individuals escaping through the square mesh windows placed in the trawl belly or in the top of the cod end (Papers V and VI) was carried out by means of top covers. These covers have more complex designs when compared to those used in cod end selectivity experiments, being made of buoyant netting material such as polyethylene, and rigged with floats to increase clearance from the escaping area, thus giving the fish the opportunity to rise above these devices before falling back into the cover cod end (Wileman et al., 1996). A specially designed top cover (Fig. 8) was used in Paper VI, following to the specifications in Wileman et al. (1996). This type of cover was first used by Larsen and Isaksen (1993), and is now strongly recommended for window or grid

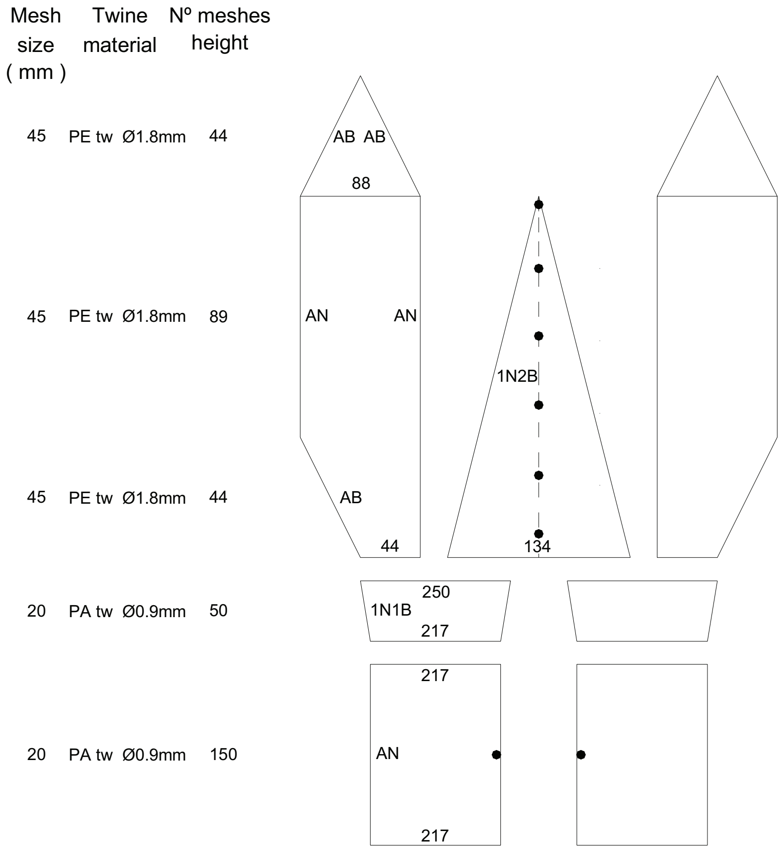


Fig. 8. Technical drawing of the top cover used in square mesh windows experiments (Paper VI). The cover was mounted over the window according to specifications in Wileman et al. (1996), and rigged with 8 floats of 2.7 kg.

selectivity experiments. In our experiments, the cover fore part was made in twisted polyethylene 45 mm mesh size, while the rear part, corresponding to the cover cod end, was identical to the trawl cod end, i.e., made in twisted polyamide 20 mm mesh size. A different type of cover (Fig. 9) was used in Paper V, made entirely of twisted polyethylene 45 mm mesh size and 1.8 mm twine thickness. The cover was rigged with floats in order to minimize possible masking effects on the window meshes.

Similarly to cod end selectivity, the selectivity estimated for windows or other sorting devices when using top covers is that of the device alone, and not the overall selectivity of the rear part of the trawl. Therefore, when using a top cover it is important to ensure that escapement is not affected between cod ends (trawl and cover cod ends) by differences in mesh size or other parameters, such as twine characteristics or number of meshes round. In other words, the selectivity should be the same in the trawl cod end and the cover to ensure that the selectivity of the device in study can be correctly estimated within the size range of the individuals retained.

In Paper V, smaller mesh sizes were used in the cover and respective cod end when compared to trawl cod ends (45 *versus* 55 mm). However, data bias related to possible overestimation of escapement were certainly compensated, at least in part, by the low hanging ratio (1:2) used at both cod end joining rows and in the cover attachment to the trawl, which ensured a high degree of mesh closeness. On the other hand, in Paper VI small mesh cod ends (trawl cod end and cover cod end) of 20 mm mesh size were used in order to guarantee that the selectivity could be esti-

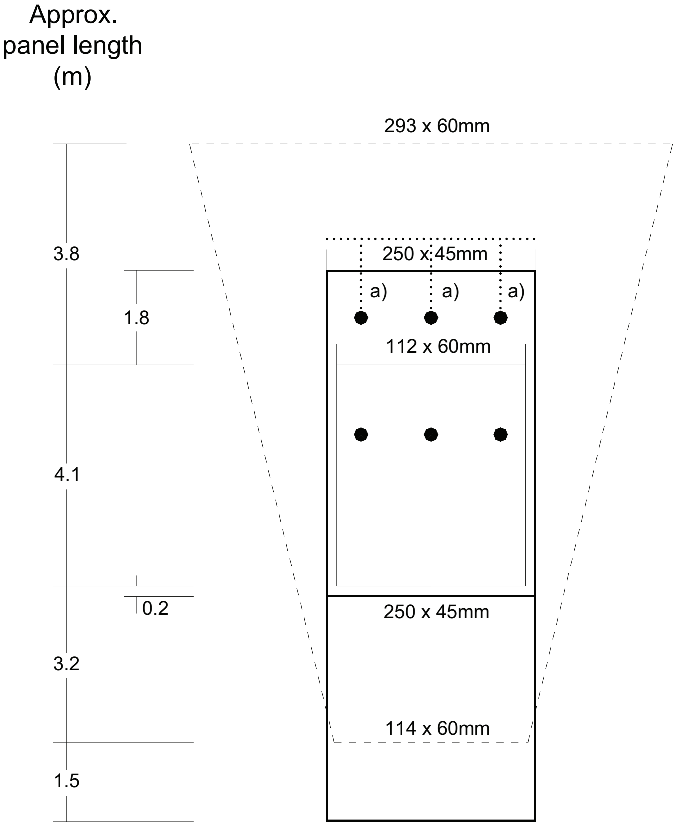


Fig. 9. Technical drawing of the top cover used in the trawl equipped with BRD's (Paper V). Thick, dashed and thin lines correspond to the cover, trawl upper panel and square mesh window, respectively. The cover was rigged with 6 floats of 2.7 kg. a) Cable length: 1.1 m

mated within the range of lower length classes for the smaller species captured. It was assumed that the escapement was minimal through the cover forepart, which was built in twisted PE of 45 mm mesh size. A smaller mesh size in this area would most probably have negative effects on the water flow through the window, making its use of doubtful justification.

2.2.3. Gear performance

During most of the hauls, trawl geometry and water speed were recorded using hydro-acoustic equipment including depth, height, spread, and a trawl speed sensor. Visual inspection of the gear was carried out only for the trawl equipped with separator panel (Paper V), when an underwater video camera installed on a remote operated vehicle was used. For this purpose, a few hauls were carried out during a previous survey at depths around 50 m (see Campos et al., 1996). At deeper waters, on crustacean fishing grounds, the visibility was reduced due to low light levels and high water turbidity generated by the passage of trawl doors and gear over the muddy bottoms. No images on the behaviour of crustacean and fish by-catch species in relation to the sorting devices could therefore be obtained.

A sonar attached to the ROV was also used during previous experiments, allowing for the recording of trawl geometry in the section where the sorting panel was installed. At trawling speeds between 2.5 and 3.0 kn approximately, the trawl height at the beginning of the separator panel slightly exceeded 1.5 m, as can be observed in Fig. 10, while at the end of the panel forepart it was about 1.4 m. After panel adjustments, the passage to the lower cod end (given by the distance measured between the trawl lower panel and the separator panel leadline), and the direct access to the upper cod end (measured as the distance between the constrictor rope and the trawl upper panel) were about 25 and 40 cm, respectively. This was in accordance with previous measurements in a 1:4 scale model of this trawl during flume tank tests (Campos et al., 1996).

2.3. Cod end selectivity

2.3.1. Estimation of selectivity parameters

Selectivity curves have been traditionally estimated for pooled data within all hauls for which controlled parameters remain unchanged, usually modelling the retention probability $r(l)$ in the cod end by means of the logistic model, where:

$$r(l) = \frac{\exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)}$$

is the probability that a fish of length l is retained, given that it entered the cod end, and $v = (v_1, v_2)^T$ the vector of parameters being estimated.

This curve is commonly described in terms of the

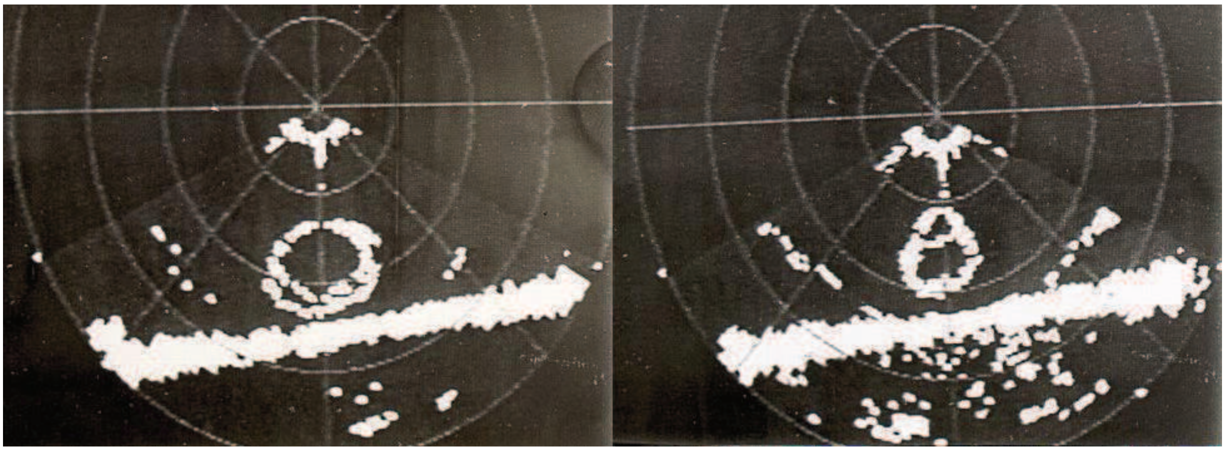

a) b)

Fig. 10. Trawl configuration at the section where the separator panel was installed. a) at the beginning of the panel forepart; b) at the level of the constrictor cable. Distance between scale rings is 1.5 m.

selectivity parameters L_{50} and SR. L_{50}, the length at 50% retention, can be obtained by solving $r(l) = 0.5$, giving $L_{50} = -v_1 / v_2$. Analogously, SR, the selection range, can be expressed by $\mathrm{SR} = 2\ln(3)/v_2$.

As previously discussed, haul to haul variation in selectivity is observed to occur when using the same net, due to uncontrolled variations in external variables such as cod end catch size, depth, sea state and bottom currents, among others, and therefore the variance of the parameters obtained from pooled data is underestimated. Fryer (1991) introduced a general framework for modelling cod end selectivity data in which between-haul variation is modelled by allowing the selectivity curves to vary randomly between hauls about a mean selectivity curve with a given probability distribution. He assumed that the parameters $v = (v_{i1}, v_{i2})^{\mathrm{T}}$, $i = 1,\ldots,H$ with H = number of hauls, are independent and multivariate normal distributed:

$$\hat{v}_i \sim N(\alpha, R_i + D),$$

with expected value $E\begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix}$

and variance matrix $R_i + D$, in which the variance matrices $\{R_i\}$ measure the within-haul variation and $\{D\}$ measures the between-haul variation in the parameters $\{v\}$.

The variance of the estimated parameters for the mean curves was shown to be more realistic when the between-haul variation is taken into account under Fryer's fixed and random effects model. Furthermore, this approach allows correction for the effects of sub-sampling in individual hauls, according to Millar (1994) who showed that for sub-sampled hauls

$$r'(l) = \frac{q\exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)} = \frac{\exp(v_1' + v_2 l)}{\exp(v_1' + v_2 l)}$$

where $q = p_1 / p_2$ is the ratio of sampling proportions in the cod end and cover respectively. Therefore, the curve fitted to the retention proportions $r'(l)$ of sub-sampled data is also logistic, with parameters $v_1' = v_1 + \ln(q)$ and v_2.

2.3.2. *Choice of hauls*

Evaluation of the potential hauls to include in the haul-by-haul analysis was based on the number of individuals in the different length classes, as well as on the range of length classes (Wileman et al., 1996). In other words, a haul was considered to be a potential candidate for the analysis provided that "sufficient" numbers of individuals were present in a wide length class range including retention proportions from 0 to 1 approximately. The final decision to keep or reject an individual haul was accomplished after curve fitting and model checking by analysis of deviance and residuals distribution. Deviance estimates higher than those expected for binomial distributed data, were observed in many of the hauls, particularly for blue whiting (Papers II and IV). This does not necessarily indicate lack of fit of the model, instead it may be attributed to overdispersion, the failure of the assumption of independence in fish cod end entrance, due to schooling behaviour (Fryer, 1991; Millar and Fryer, 1999). Violation of this assumption was compensated for by multiplying the variance matrix of the estimated parameters by the overdispersion factor (ratio of model deviance to the corresponding degrees of freedom) (Wileman et al., 1996).

2.3.3. *Haul-by-haul versus pooled data analysis*

Whenever the data structure allows for the estimation of selectivity on a haul-by-haul basis, this approach should be followed in selectivity analyses. However, when many species occur together in relatively low quantities each, as is often the case in south European waters and, besides, length classes captured are not the same in all the hauls, since fish of different age classes live at different depths, a typical haul is formed by a relatively high number of species, each of them sometimes poorly represented in terms of quantities captured, and the number of individual hauls with which it is possible to work with can be reduced down to a point where the estimation of mean selectivity curves is not possible. In that case the selectivity can be estimated by pooling data by length class across all the hauls for which the variables under test remain unchanged, but all the information on between haul variation is obviously lost.

In the present case, pooling the data by cod end mesh size/mesh configuration allowed the estimation of selectivity curves for a number of cases where the Fryer method was not applicable (Table 4).

Table 4
Methods for the estimation of the selectivity. F: haul-by-haul analysis; P: pooled data. The numbers of hauls used in the estimation are in brackets.

Crustacean trawling	55D				60D				70D				55S			
Rose shrimp (I)	F	(7)	P	(25)	F	(7)	P	(22)	F	(11)	P	(24)	F	(9)	P	(19)
Norway lobster (I)	F	(5)	P	(34)	F	(7)	P	(33)	F	(7)	P	(31)	F	(10)	P	(20)
Blue whiting (II)	F	(7)	P	(38)	F	(14)	P	(30)	F	(6)	P	(30)	F	(5)	P	(23)
Horse mackerel (II)	-		P	(28)	-		P	(21)	-		P	(22)	-		P	(20)
European hake (II)	-		P	(36)	-		P	(30)	-		-		-		-	(23)
Red shrimp (II)	-		P	(19)	-		P	(16)	-		P	(10)	-		P	(4)

Fish trawling	65D				70D				80D				65S			
Blue whiting (IV)	F	(10)	P	(13)	F	(5)	P	(14)	F	(6)	P	(18)	-		-	
Horse mackerel (III)	-		P	(8)	-		P	(4)	-		P	(6)	-		P	(7)
Horse mackerel (IV)	-		-		-		-		-		-		F	(5)	P	(10)
European hake (III)	-		-		-		P	(4)	-		P	(8)	-		P	(6)
European hake (IV)	F	(5)	P	(13)	F	(5)	P	(18)	-		P	(11)	-		P	(10)
Axillary seabream (III)	-		-		-		-		-		P	(8)	-		P	(7)
Four-spot megrim (IV)	-		P	(13)	-		P	(18)	-		P	(18)	-		P	(10)

2.3.4. *Selectivity models*

Fryer (1991) extended his model in order to assess the influence of fixed effects (controlled net changes) as well as the random variation between hauls. This allows the estimation of the individual contribution of some explanatory variables (the gear characteristics in study and other external variables that can play a role in between-haul variation) on the selectivity parameters. Under these conditions,

$$\hat{v}_i \sim N(X_i\alpha, R_i + D)$$

where the expected value $E\begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = X_i\alpha$, X_i being the design matrix of the q explanatory variables for haul i:

$$X_i = \begin{pmatrix} x_{i11} & x_{i12} & \cdots & x_{i1q} \\ x_{i21} & x_{i22} & \cdots & x_{i2q} \end{pmatrix}$$

and $\alpha = (\alpha_1, \alpha_2, ..., \alpha_q)^{\mathrm{T}}$ the vector which determines the direction and magnitude of the influence of these variables on the selectivity parameters.

The estimation of selectivity parameters was carried out modelling the retention as a logistic function of size. In Papers I and II, the maximum likelihood estimation of the selectivity parameters for individual hauls was carried out using an Excel spreadsheet (Tokai, 1997), modified to allow for the estimation of v_i and R_i for sub-sampled hauls, according to Millar (1994), as well as of 95% confidence intervals for the selectivity parameters (Wileman et al., 1996), while the software CC2000 (Constat) was used for the same purpose in Papers III and IV. Models that incorporate between-haul variation, such as mean selectivity curves and fixed and random models, were estimated using the software ECModeller (ConStat) that follows the methodology proposed by Fryer (1991). In the latter models, the selectivity parameters L_{50} and SR were used as response variables instead of the generic parameters v_1 and v_2, in order to simplify model interpretation. When using generic parameters, the effects of the same explanatory variable in both v_1 and v_2 are often significant, and of different signs, making the evaluation of their influence in both L_{50} and SR difficult.

2.3.5. *Girth versus length selectivity*

Cod end selectivity is usually modelled as a function of body length. However, it ultimately depends on fish shape and how it adapts to mesh opening, a fact that has long been reported (Baranov, 1948; Margetts, 1957; Messtorff, 1958; Efanov et al., 1987; Shevtsov, 1988). For round fish species, the critical dimension while trying to escape through a mesh has usually been assumed to be its maximum girth. However, no studies have been found where trawl selectivity was estimated as a function of body girth, with the exception of Özbilgin (1998), who investigated the effect of seasonal variation in cod end selectivity for haddock. This is due to the fact that body length is much easier to measure. Since length is usually highly correlated with girth, length-girth relationships can be used to plot selectivity as a function of girth, without much concern for the fact that the girth variance for a given length is not taken into account. Tokai and Omoto (1994) and Liang et al. (1999) have plotted retention in cod end versus G_{max}/mesh perimeter for a number of fish species in Japanese waters, directly comparing the selectivity for the different species by bringing the corresponding maximum girths to the same scale. This has allowed for a better understanding of the mechanisms of escapement through cod end meshes for the species in study.

The same procedure was followed in Paper III, for the horse mackerel, the European hake and the axillary seabream captured simultaneously off the Portuguese south west coast, for which large differences in selectivity for fish of the same size were observed between species. Girth/length relationships were estimated using data obtained during the sea trials for the species in study, and considering that length was highly correlated with girth, selectivity-at-length was converted into selectivity-at-girth, allowing for a better explanation of the selection patterns observed.

2.4. Selectivity of separator panels and square mesh windows

While in Papers I to IV cod end selectivity parameters were estimated, in Paper V it was not possible to evaluate the length-dependence of individuals retained by the separator panels. The reason was that the only available information in this case was the numbers of individuals by length class captured in the lower and upper cod ends, and the cover, while the total numbers entering the rear trawl section at the different levels remain unknown.

The evaluation of the sorting panels as by-catch excluders was then carried out for the most important species by comparing, for the different groups of hauls corresponding to the different combinations of BRD's tested, the percentage of the total catch reaching the upper level of the trawl, and therefore having the chance of contacting with the square mesh window ("*contact*" fraction), corresponding to the sum of catches in the upper cod end and cover. Similarly, the evaluation of square mesh windows was carried out by comparing, for the same combinations, the catch fraction retained in the cover with that reaching the upper trawl level, termed "*excluded after contact*". The whole sorting system (separator panel + window) was evaluated by comparing the percentage of the total catch that was "*excluded*" (i.e., escaped through the square mesh window) in the different test situations. The above terminology is used in Paper V and throughout the discussion that follows. In Paper VI, where only square mesh windows were used, the escape percentages were compared for the two window positions.

In these data, the usual assumptions for parametric tests are not met, either due to the fact that the separation percentages within groups do not follow normal distributions, and the variances in the groups were observed to be heterogeneous. The null hypothesis of no difference among these percentages at the different groups of hauls was therefore tested through non-parametric analysis of variance by a rank test (Kruskal-Wallis test, Conover, 1980) when more than two groups were compared, or Wilcoxon test, (Conover, 1980), when comparisons were only between two groups. Whenever significant differences were found between more than two groups, a multiple comparison test (Conover, 1980) was used to determine which pairs of groups differed significantly.

Length-dependence of individuals escaping through the square mesh windows could on the other hand be established, since the catch composition available to the window is known, being the sum of the catches in the upper cod end and the cover, while the escapees are collected by the window cover. For a number of cases, length-dependence of individuals escaping through the windows could be modelled. However, unlike cod end selectivity, where the entire population entering is submitted to the selection process, the size-selection by a sorting device such as a window is dependent on whether the fish encounter it. Underwater observations (Glass and Wardle, 1995) have shown that a significant proportion of fish that enter a net equipped with a window may pass below the window without being aware of it. Therefore, the probability $r(l)$ that a fish of length l is retained by the window, i.e., do not cross the window meshes, given that it was found in the upper trawl level, was modelled according to the three-parameter model:

$$r(l) = \frac{p * \exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)} + (1 - p)$$

(Tokai et al., 1996; Tokai, 1988; Zuur et al., 2001), where p is the estimated probability of encountering the window.

The encounter probability model was applied to horse mackerel and rose shrimp pooled data, where clear length-dependence was observed in the retention by the 70 mm mesh size window (Paper V), while in the 100 mm windows (Papers V and VI), length-dependence was much less obvious, and therefore the selectivity could not be estimated. Parameters were estimated by maximum likelihood using an Excel spreadsheet.

2.5. Departure from commercial conditions

Selectivity data should be obtained under commercial conditions to be representative of commercial activity. However, departure from commercial conditions can seldom be avoided. Along this work, the use of covers illustrates this situation, but other sources of variation can be identified when comparing to the commercial fishing activity. Tow duration was set to one hour in most experiments, a value below that of normal commercial practice, in which tow duration is usually around two hours when trawling for fish, and up to several hours when crustaceans are the target species. This contributed to lower catches when compared to commercial fishing. The testing of separator panels and square mesh windows in Paper V was, on the other hand, closer to commercial conditions. Here, part of the trials were carried out onboard a commercial vessel, while in the remaining, the R/V "Mestre Costeiro", a stern trawler with size and engine power similar to most vessels engaged in crustacean trawling, was used to tow a commercial trawl. The duration of hauls in these experiments ranged from 1 to over 3 hours, and over 65% of the hauls were of at least 2 hours duration, which is much more representative of commercial fishing practice.

3. Results

3.1. Cod end selectivity

The selectivity parameters L_{50} and SR estimated for all species in cod end selectivity experiments (Papers I to IV) are presented in Table 5. L_{50} was generally observed to increase with increasing mesh size. However, exceptions did occur, for the Norway lobster (Paper I), as well as for hake and blue whiting (Paper IV), for which L_{50} decreased with increases in cod end mesh size from 55 to 60 mm, and from 70 to 80 mm diamond mesh, respectively. Increase in SR with increasing mesh size was less obvious. For the rose shrimp (Paper I) a lower SR estimate was obtained in the 70 mm diamond cod end when compared to the 60 mm one, while for red shrimp (Paper II) SR decreased with successive increases in mesh size. Also, for horse mackerel (Papers II and III) and hake (Paper IV) lower SR estimates were associated to the use of 60 and 70 mm diamond cod ends when compared to the 55 and 65 ones.

Positive effects of changing mesh configuration from 55 mm diamond to 55 mm square mesh were observed in L_{50} for the crustaceans, as well as for horse mackerel (Papers II and III), blue whiting (Paper II) and hake (Paper IV), for which comparative selectivity data were obtained between diamond and square mesh cod ends, while corresponding increases in SR were also observed for all these species except the red shrimp. Of all the species studied, the four-spot megrim was the one for which the use of the square mesh was found to be associated to reduction both in L_{50} and SR. This is in accordance with previous results from selectivity experiments for sole (Fonteyne and M'Rabett, 1992) and American plaice (Walsh et al., 1992).

The observed fluctuations in L_{50} and SR when increasing mesh size or changing mesh configuration from diamond to square mesh, can be better understood in Figs. 11 to 16, referring to the exploratory analysis of these data. Scatterplots are shown between a number of variables that are expected to explain

Table 5
Selectivity parameters L_{50} and SR for the cod ends in study using haul-by-haul analysis (F) and pooled data (P). 95% CI are in brackets.

Crustacean trawling	Method of estimation	55D		60D		70D		55S	
		L50	SR	L50	SR	L50	SR	L50	SR
Rose shrimp (I)	F	21.8	5.7	24.0	9.3	27.1	8.9	27.1	9.3
		(20.5-23.1)	(4.5-6.9)	(22.8-24.9)	(7.7-10.8)	(26.2-27.7)	(6.7-11.1)	(26.2-27.9)	(8.6-10.0)
Norway lobster (I)	F	27.1	6.1	25.8	8.0	28.1	9.4	34.7	16.0
		(25.9-28.2)	(4.7-7.5)	(23.9-28.1)	(6.8-9.2)	(26.6-29.8)	(8.0-10.8)	(33.1-36.4)	(13.4-18.6)
Blue whiting (II)	F	23.0	3.7	25.9	4.1	27.3	5.0	30.2	4.5
		(22.3-23.9)	(2.6-4.9)	(24.9-26.8)	(3.7-4.6)	(25.6-28.7)	(4.2-5.9)	(29.3-30.7)	(2.7-6.2)
Horse mackerel (II)	P	18.0	3.8	19.8	3.6	21.9	4.9	21.7	5.0
		(17.9-18.1)	(3.5-4.0)	(19.6-20.0)	(3.2-4.1)	(21.4-22.4)	(4.2-5.7)	(21.2-22.2)	(4.5-5.6)
European hake (II)	P	15.9	3.0	17.4	3.8	-	-	-	-
		(15.7-16.1)	(2.7-3.3)	(17.1-17.7)	(3.1-4.5)	-	-	-	-
Red shrimp (II)	P	13.8	22.6	24.6	11.5	29.8	9.8	32.3	9.1
		(8.5-19.1)	(17.4-27.8)	(23.4-25.8)	(10.3-12.8)	(28.6-31.1)	(8.3-11.3)	(31.6-33.0)	(8.2-10.1)
Fish trawling		65D		70D		80D		65S	
Blue whiting (IV)	F	22.7	3.5	24.1	3.8	22.5	4.6	-	-
		(21.7-23.5)	(3.0-4.4)	(22.4-26.1)	(2.9-5.5)	(21.3-24.4)	(4.4-6.5)	-	-
Horse mackerel (III)	P	14.4	3.3	14.7	2.9	16.0	3.7	21.9	8.3
		(14.2-14.6)	(3.0-3.6)	(14.5-15.0)	(2.5-3.3)	(15.9-16.2)	(3.2-4.2)	(21.1-22.8)	(6.8-9.8)
Horse mackerel (IV)	F	-	-	-	-	-	-	27.3	3.4
		-	-	-	-	-	-	(26.1-28.6)	(2.8-3.9)
European hake (III)	P	-	-	17.0	3.0	18.3	4.2	32.4	8.2
		-	-	(16.5-17.5)	(2.2-3.7)	(17.9-18.7)	(3.6-4.7)	(30.6-34.2)	(6.3-10.2)
European hake (IV)	P	17.0	5.2	19.2	3.9	18.8	4.4	25.0	5.6
		(16.7-17.3)	(4.5-5.9)	(19.0-19.4)	(3.5-4.4)	(18.6-19.0)	(3.9-4.9)	(23.7-26.2)	(4.3-6.9)
Axillary seabream (III)	P	-	-	-	-	13.9	7.4	19.6	3.6
		-	-	-	-	(13.4-14.4)	(5.8-8.9)	(19.1-20.1)	(2.8-4.4)
Four-spot megrim (IV)	P	16.7	3.5	17.5	4.5	21.0	6.5	16.0	2.8
		(16.0-17.3)	(2.6-4.3)	(16.8-18.2)	(3.5-5.6)	(19.6-22.3)	(4.9-8.1)	(15.5-16.4)	(2.1-3.4)

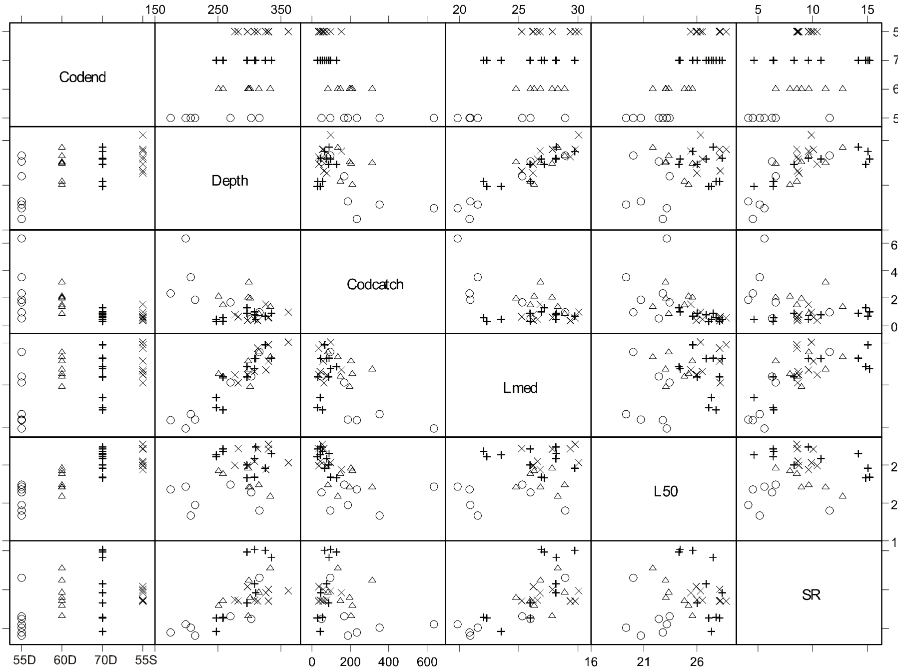


Fig. 11. Rose shrimp (Paper I) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); Lmed: mean length of individuals (mm); L_{50} and SR in mm.

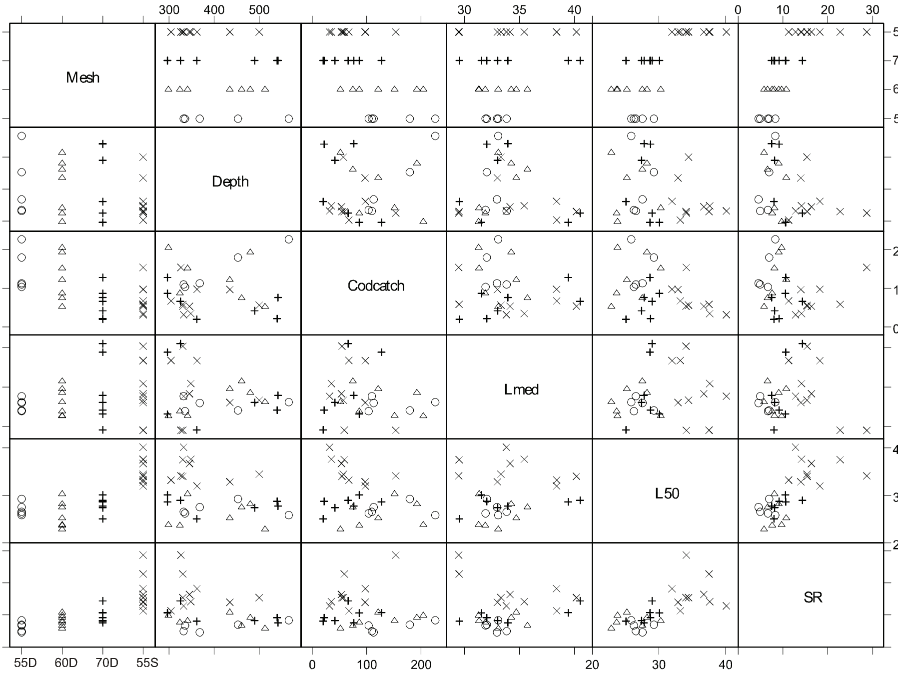


Fig. 12. Norway lobster (Paper I) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); Lmed: mean length of individuals (mm); L_{50} and SR in mm.

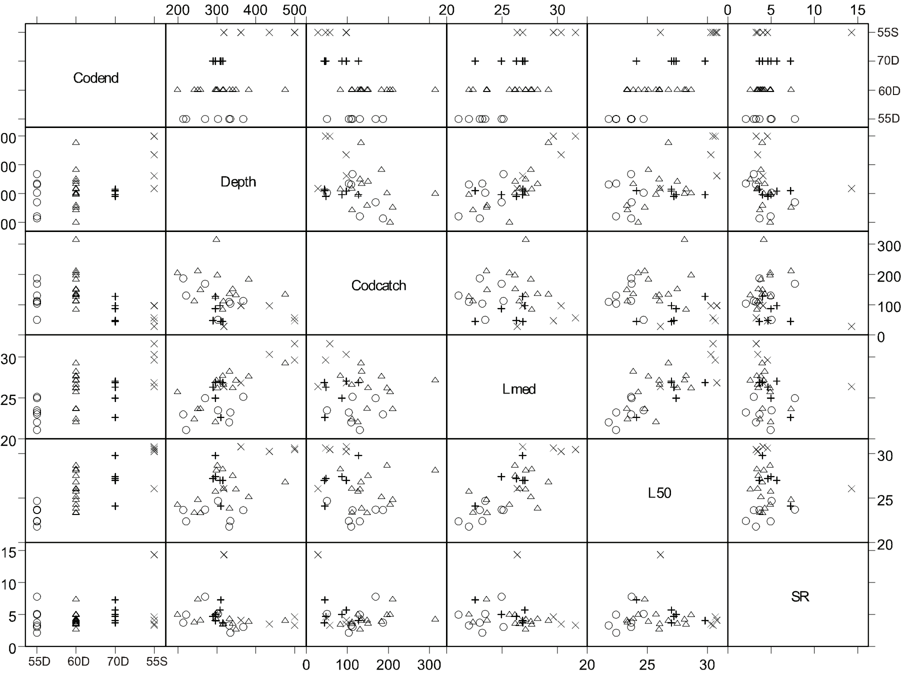


Fig. 13. Blue whiting (Paper II) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); L_{med}: mean length of individuals (cm); L_{50} and SR in cm.

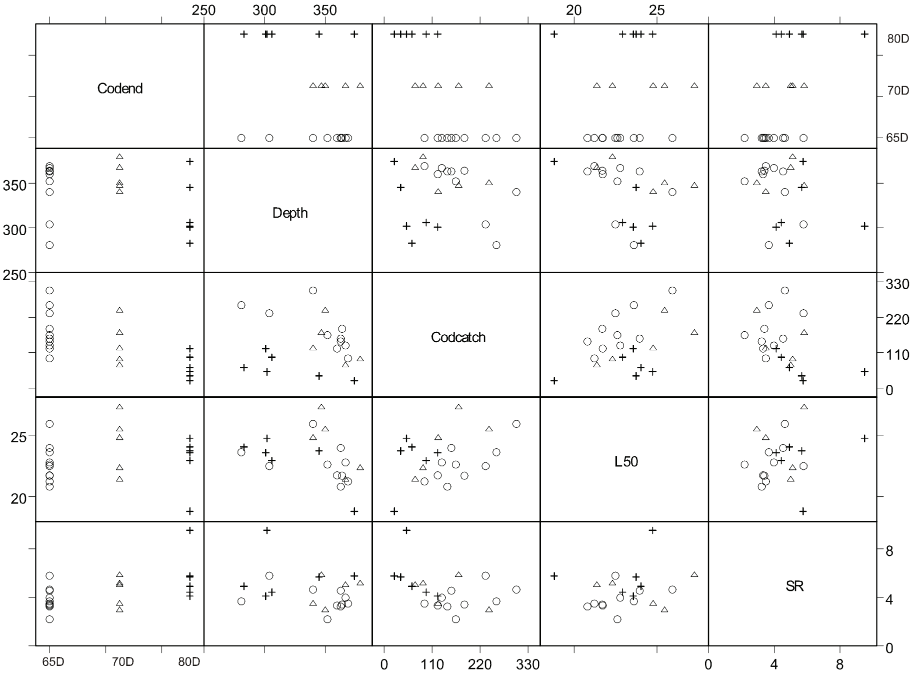


Fig. 14. Blue whiting (Paper IV) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); L_{50} and SR in cm.

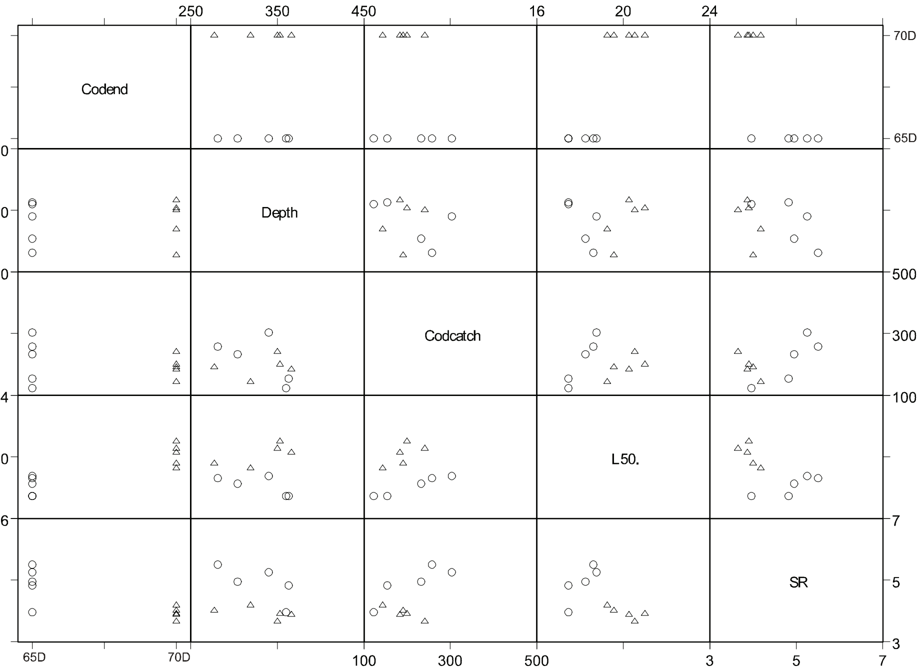


Fig. 15. Hake (Paper IV) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); L_{50} and SR in cm.

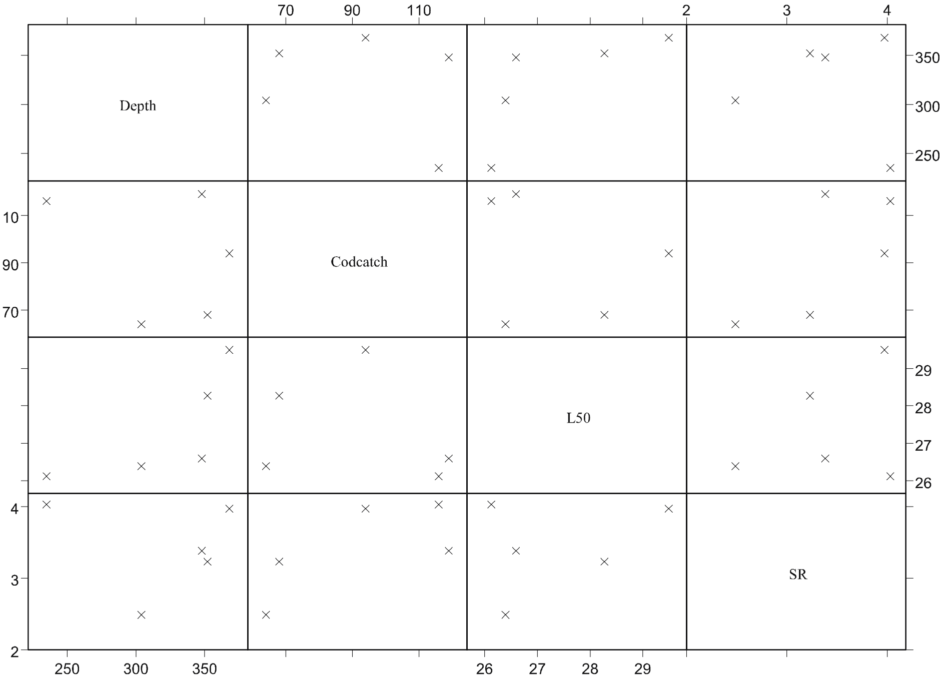


Fig. 16. Horse mackerel (Paper IV) – scatterplots. Depth: towing depth (m); Codcatch: cod end catch (kg); L_{50} and SR in cm.

part of the observed between-haul variation of the selectivity parameters L_{50} and SR for those species and mesh sizes for which selectivity could be estimated on a haul-by-haul basis. Besides the variables tested, mesh size and mesh configuration, cod end catch and towing depth were included.

Length-dependence on depth was investigated for all species captured over a wide depth range as was the case for rose shrimp, Norway lobster and blue whiting in crustacean fishing grounds, through the estimation of the mean length per haul ("Lmed").

Before the effects of these variables on L_{50} and SR are discussed, it must be noted that neither the range of cod end catches, nor the depth intervals analysed are the same for all cod ends. For all the species in study, the increase in cod mesh size or change in mesh configuration to square mesh was associated with an expected decrease in cod end catch, since higher mesh sizes and square meshes are by definition more selective. Similarly, for a number of species (rose shrimp, Fig. 11; blue whiting, Figs. 13 and 14), some differences exist regarding the depth interval of the individual hauls carried out with the different cod ends.

Of these variables, only depth was found to play a significant role in between-haul variation for rose shrimp by positively affecting SR (Fig. 11). Depth is likely to affect SR by conditioning the mean length of the individuals captured. For the Norway lobster (Fig. 12), a positive relationship was recorded between SR and cod end catch weight, which is more evident for the 55 and 60 mm diamond cod ends with higher catch range. For blue whiting (Fig. 13) there is also a clear effect of cod end catch in L_{50} for the 55 and 60 mm diamond cod ends. For blue whiting, hake and horse mackerel captured in fish trawling (Figs. 14 to 16), no relationship was found between depth and L_{50} or SR, which is not surprising given the narrow depth ranges fished, while the increase in cod end catch was associated with a corresponding increase in L_{50}.

Considering the exploratory analysis above, the effects on both L_{50} and SR of the most significant variables were estimated by using fixed and random effects models (Fryer, 1991; Millar and Fryer, 1999). Selectivity models have been proposed (Table 6) which relate L_{50} and SR to the variables tested, mesh size and mesh configuration, and also to cod end catch and fishing depth. The direction, magnitude and relative importance of the estimated effects for all variables are given in Table 7. Mesh size was the

Table 6
Selectivity models proposed for the most important species. m_i – mesh size; t_i – mesh configuration; d_i – fishing depth; c_i – cod end catch.

Species	Models proposed
Rose shrimp (Paper I)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_2 m_i + \alpha_3 t_i \\ \alpha_1 + \alpha_4 d_i \end{pmatrix}$
Norway lobster (Paper I)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_3 t_i \\ \alpha_2 + \alpha_4 t_i + \alpha_5 m_i + \alpha_6 c_i \end{pmatrix}$
Blue whiting (Paper II)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_1 m_i + \alpha_3 t_i + \alpha_4 d_i + \alpha_5 c_i \\ \alpha_2 m_i \end{pmatrix}$
Blue whiting (Paper IV)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_2 m_i + \alpha_4 c_i \\ \alpha_3 m_i \end{pmatrix}$
European hake (Paper IV)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_3 m_i + \alpha_5 c_i \\ \alpha_2 + \alpha_4 m_i \end{pmatrix}$
Horse mackerel (Paper IV)	$E\begin{pmatrix} L_{50} \\ SR \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 c_i \end{pmatrix}$

Table 7
Parameter estimates along with the respective standard errors and t-values.

Parameter	Effect on	Parameter estimate	Standard error	t-value
Rose shrimp (Paper I)				
constant	SR	-3.543	1.51	-2.3
mesh size	L_{50}	0.380	4.06×10^{-3}	95.9
mesh configuration	L_{50}	5.401	0.47	11.4
depth	SR	0.042	5.41×10^{-3}	7.7
Norway lobster (Paper I)				
constant	L_{50}	27.213	0.52	52.7
constant	SR	-16.494	3.47	-4.8
mesh configuration	L_{50}	7.403	0.93	8.0
mesh configuration	SR	9.025	1.09	8.2
mesh size	SR	0.348	5.19×10^{-2}	6.7
cod end catch	SR	0.024	4.70×10^{-3}	5.2
Blue whiting (Paper II)				
mesh size	L_{50}	0.318	2.31×10^{-2}	13.730
mesh size	SR	0.065	2.56×10^{-3}	25.155
mesh configuration	L_{50}	6.016	1.03	5.827
depth	L_{50}	0.012	4.28×10^{-3}	2.879
cod end catch	L_{50}	0.017	4.40×10^{-3}	3.829
European hake (Paper IV)				
constant	L_{50}	-8.394	2.98	-2.8
constant	SR	13.244	3.53	3.8
mesh size	L_{50}	0.381	4.37×10^{-2}	8.7
mesh size	SR	-0.136	5.28×10^{-2}	-2.6
cod end catch	L_{50}	0.011	2.22×10^{-3}	4.9
Blue whiting (Paper IV)				
constant	L_{50}	10.326	4.54	2.3
mesh size	L_{50}	0.141	5.83×10^{-2}	2.4
mesh size	SR	0.055	2.72×10^{-3}	20.4
cod end catch	L_{50}	0.021	5.28×10^{-3}	4.0
Horse mackerel (Paper IV)				
constant	L_{50}	27.034	5.36×10^{-1}	50.4
cod end catch	SR	0.037	4.72×10^{-3}	7.8

variable that most affected selectivity for all species except the Norway lobster, as shown by the t-values in Table 7. This variable mainly affected L_{50}, for rose shrimp and hake (Paper IV), while for blue whiting its main effect was on SR, in the two models proposed for this species (Papers II and IV). For the Norway lobster, mesh configuration was found to be the most important variable, both on L_{50} and SR. Positive effects of mesh size were always estimated, either in L_{50} or SR, denoting an increase in the selectivity parameters with increasing mesh size, with the exception of hake (Paper IV), for which a decrease in SR was estimated. Similarly, positive effects of mesh configuration were observed, only on L_{50} for rose shrimp (Paper I) and blue whiting (Paper II), and on both L_{50} and SR for Norway lobster. In Paper IV the effects in selectivity of changing mesh configuration could not be evaluated since the data structure did not allow a haul-by-haul analysis. This was due to almost total escapement of blue whiting and hake from the square mesh cod end, while horse mackerel was entirely retained in all cod ends except the square mesh one, which clearly indicates higher selective properties of square mesh for these species as well. Positive effects of external variables such as depth, for rose shrimp and blue whiting, and cod end catch, for all species except rose shrimp, on selectivity, were estimated in these models, but tended to be less important when compared to mesh size or mesh configuration. While for fish species (except for horse mackerel) the effects on L_{50} of these variables were estimated, for crustaceans they affected mostly SR.

Other commercial species were sampled along these surveys for which selectivity parameters were not estimated. For most, this was either due to low abundance in most cod ends or inadequate data structure, while a number of non-commercial species such as small shrimps (the arrow shrimp and the Atlantic mud shrimp, *Solenocera membranacea*), the boarfish and the longspine snipefish were not size-sampled. For these species, the selective properties of the different cod ends were separately examined for the different data sets, comparing their total weights at the cod ends and covers.

Fig. 17 summarises the results for crustacean trawling (Papers I and II), while Figs. 18 and 19 account for the same comparisons for fish trawling at the shallow (Paper III) and deep (Paper IV) groundfish assemblages of the south-west coast, respectively.

Several groups can be identified on the basis of their escaping ability through the different cod ends. A first group comprises the small shrimps captured in crustacean trawling, that have almost entirely escaped, along with the longspine snipefish in fish trawling, captured in the 80 mm diamond and 65 mm square mesh cod ends. The second group accounts for those species completely (or almost completely) retained in all mesh sizes, such as the monkfish *Lophius budegassa*, the striped red mullet, *Mullus surmuletus* and the greater forkbeard, *Phycis blennoides*, that were captured as by-catch in crustacean trawling, as well as the seabreams, the rockfish, *Helicolenus dactylopterus*, the small-spotted dogfish, *Scyliorhinus canicula*, the rays, *Raja* spp. the john dory, *Zeus faber*, and, surprisingly, the common octopus. For most species within this group, with the exception of the latter, high retention can be explained by higher fish size and/or girth dimensions when compared to mesh dimensions. Round-bodied fish including hake and blue whiting, as well as fish more elliptical in shape, such as horse mackerel and the axillary seabream, for which the selectivity has been estimated, are also included in Figs. 17 to 19, where the selection patterns already described can be easily identified.

The two main discard species, blue whiting and the longspine snipefish, have almost totally escaped when 80 mm diamond and 65 mm square mesh cod ends were used in fish trawling, while 68% of the boarfish escaped from the square mesh cod end. In crustacean trawling, where smaller mesh sizes were used, 61 and 88% of blue whiting escaped through the 70D and 55S cod ends respectively, while for boarfish these figures were lower (50 and 34%) for both cod ends.

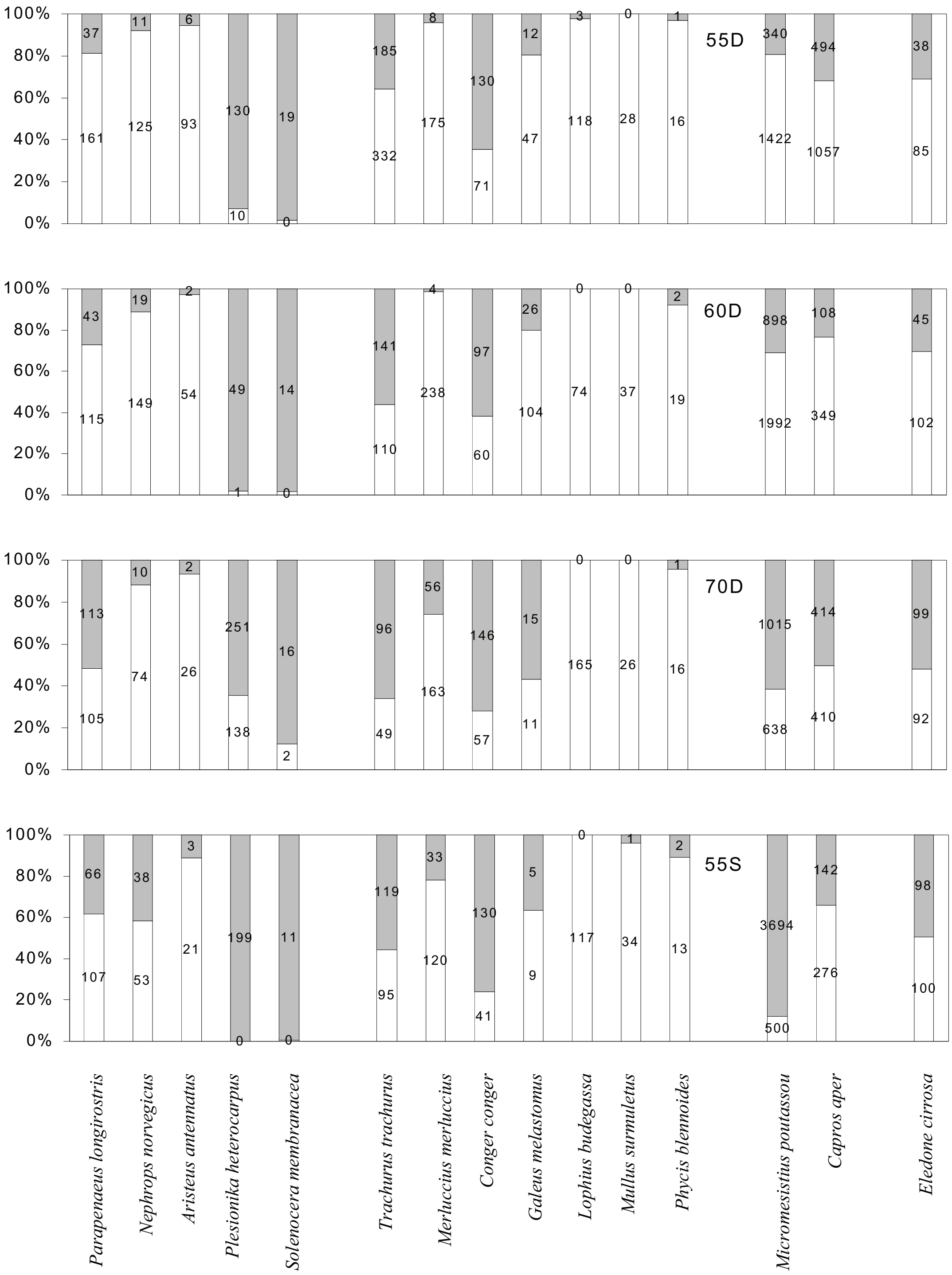


Fig. 17. Percentages, in weight, at the cod end and cover for the most captured species in crustacean trawling (Papers I and II).

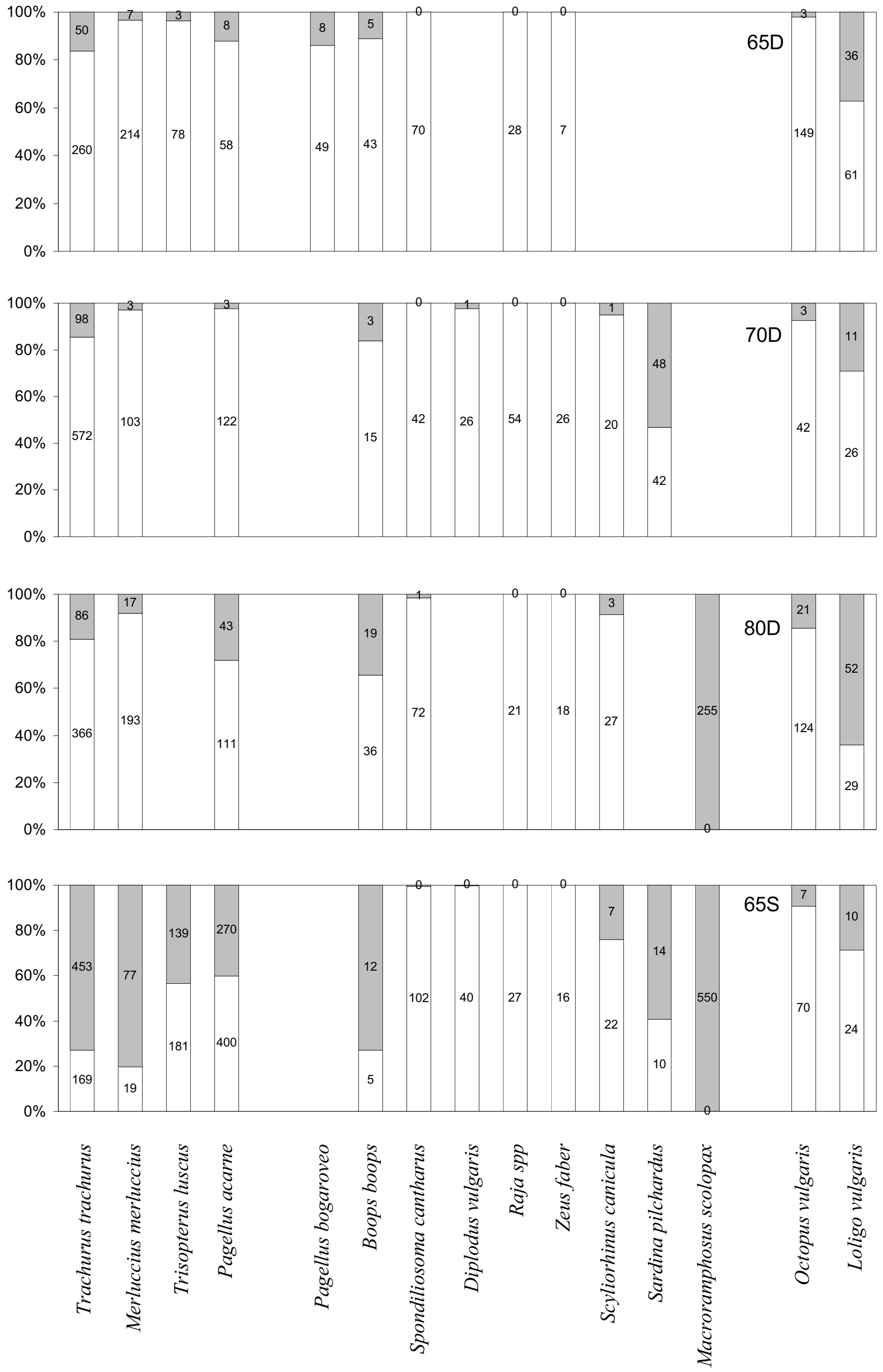


Fig. 18. Percentages, in weight, at the cod end and cover for the most captured species in the shallow groundfish assemblage at the south-west coast (Paper III).

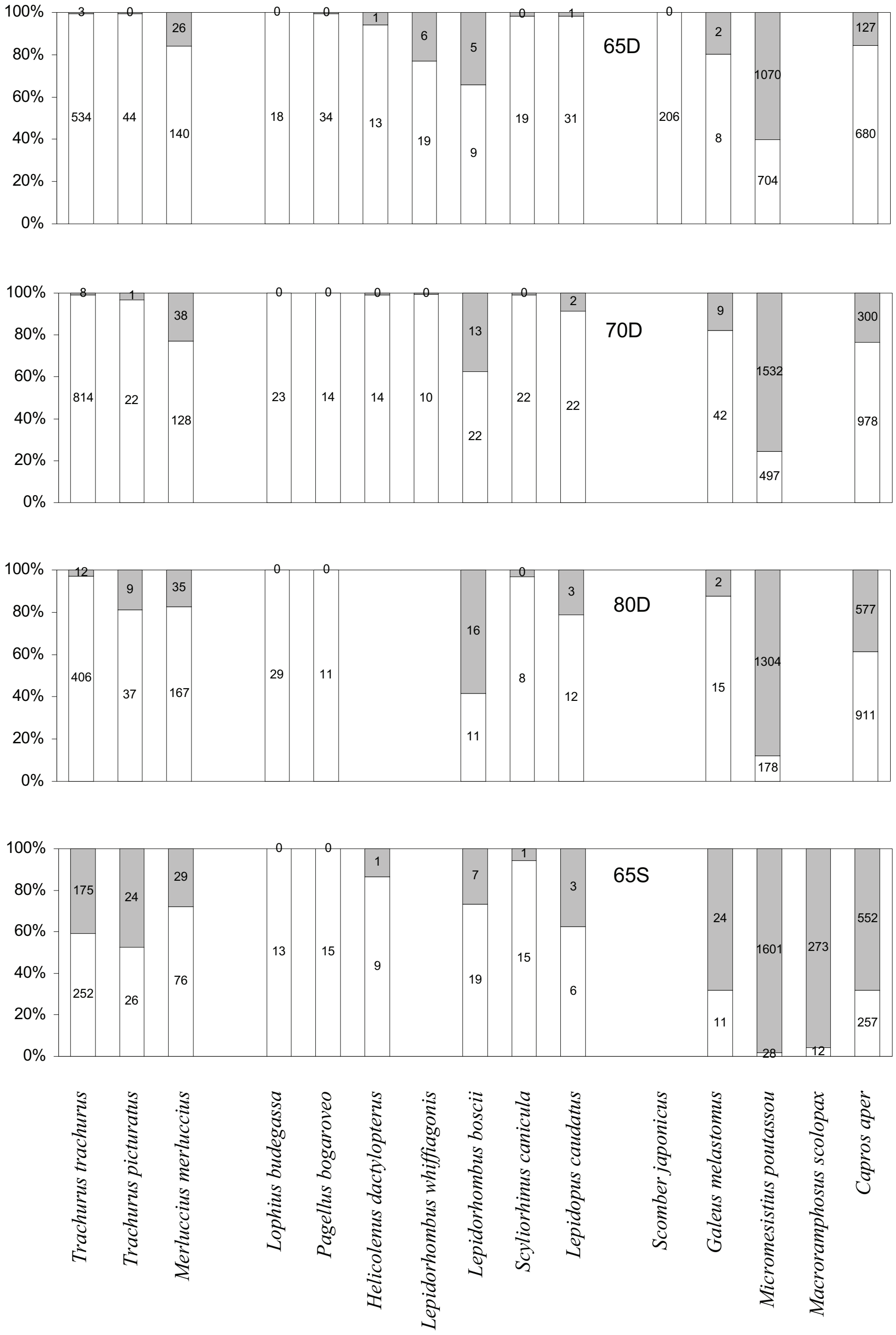


Fig. 19. Percentages, in weight, at the cod end and cover for the most captured species in the deep groundfish assemblage at the south-west coast (Paper IV).

3.2. Selectivity of trawls equipped with by-catch reduction devices

The average percentage values in weight estimated for the different catch fractions: "*excluded*", "*contact*" and "*excluded after contact*" are shown for the different combinations of BRD's in Table 8, which summarises the results presented in Paper V. Situations where statistically significant differences among groups were found are in boxes, suggesting that reduction in the sorting panel mesh size from 120 to 80 mm (group 3), increase in the window mesh size from 70 to 100 mm (groups 2 and 3) or that panel removal (group 4) affected contact and exclusion. The reduction in panel mesh size significantly increased *contact* with the window for rose shrimp, Norway lobster and blue whiting, while *exclusion after contact* was not generally affected by the increase in window mesh size, except in the case of boarfish.

Significant differences in the percentages of *excluded* among groups when the whole sorting system

Table 8
Average catch percentages (in weight) excluded and in contact with the square mesh window, for the four groups of hauls in Paper V. Coefficients of variation (CV = std/average*100) are in brackets. The situations where significant differences in these percentages were estimated, are in boxes. Different types (bold and normal) differentiate groupings.

	Average %					
Groups	*Excluded*		*Contact*		*Excluded after contact*	
Rose shrimp						
1	5.6	(116%)	14.2	(83%)	36.5	(35%)
2	4.3	(102%)	9.5	(46%)	39.7	(88%)
3	**27.8**	(33%)	**55.6**	(15%)	50.9	(36%)
4	**24.3**	(28%)				
Norway lobster						
1	0.2	(173%)	0.9	(173%)	7.8	(173%)
3	1.6	(43%)	**38.8**	(19%)	3.9	(29%)
4	0.9	(46%)				
Horse mackerel						
1	34.1	(51%)	**68.6**	(12%)	48.1	(41%)
2	33.4	(57%)	51.4	(21%)	60.3	(49%)
3	72.3	(36%)	**91.0**	(6%)	79.4	(35%)
4	26.3	(18%)				
Blue whiting						
1	69.6	(15%)	81.3	(8%)	85.4	(10%)
3	70.9	(20%)	**97.1**	(4%)	72.8	(19%)
4	66.9	(25%)				
Boarfish						
1	9.7	(90%)	77.3	(25%)	12.0	(70%)
2	**41.5**	(60%)	67.3	(31%)	**56.5**	(42%)
3	**44.2**	(63%)	78.8	(21%)	**53.0**	(49%)
4	16.9	(28%)				

is considered were found only for rose shrimp, indicating that exclusion was affected by increased contact with the window when the separator panel mesh size was reduced; and for boarfish, where differences in exclusion were, on the other hand, found to be related with differences in the window mesh size. Contrary to what was expected, removal of the separator panel was not associated with any further decrease in the exclusion for rose shrimp, with the *excluded* fraction similar to that recorded when the 80 mm separator panel was used. On the other hand, it lowered considerably the escapement of boarfish.

Overall, these results indicate active escape behaviour only for blue whiting, with the *excluded* fraction attaining values close to 70% in all the BRD combinations, including the square mesh window used alone.

The results presented in Paper VI are summarised in Table 9. Significant differences were found in escapement between SMW1 and SMW2 for all species except the rose shrimp and the blue jack mackerel, *Trachurus picturatus*, with higher escapement when the square mesh window was placed on the top of the cod end. However, only blue whiting and blue jack mackerel showed active escape behaviour, as indicated by the escape rates given in Table 9. The remaining species were excluded in extremely low amounts.

Selectivity parameters could not be estimated in these experiments except for horse mackerel and rose shrimp in the 70 mm square mesh window used together with the separator panel of 120 mm mesh size (Paper V), where retention was observed to be length-dependent. For both species, p, the probability of encountering the window, was estimated to be 1, and therefore the window retention was found to follow a logistic model with parameters v_1 and v_2, similarly to cod end retention. This seems to indicate that all the fish reaching the upper level of the trawl encountered the window. SF estimates for both species (3.1 and 0.36 respectively) indicate lower selectivity when compared with previous estimates for the same species (3.9 and 0.48) in 55 mm cod ends entirely made of square meshes (Papers I and II).

Table 9
Average catch percentages (in numbers and weight) escaping through the square mesh window, for the two groups of hauls SMW1 and SMW2 in Paper VI. Coefficients of variation (CV = std/average*100) are in brackets. The situations where significant differences in these percentages between the two groups were estimated are in boxes.

	Average % excluded			
Groups	N°		Weight	
Rose shrimp				
SMW1	11.1	(69%)	11.0	(0.63)
SMW2	7.9	(50%)	10.6	(0.63)
Horse mackerel				
SMW1	$\boxed{0.8}$	(127%)	$\boxed{1.0}$	(115%)
SMW2	$\boxed{8.0}$	(38%)	$\boxed{8.0}$	(40%)
Blue jack mackerel				
SMW1	20.7	(49%)	19.7	(46%)
SMW2	46.3	(54%)	48.2	(53%)
Blue whiting				
SMW1	$\boxed{26.8}$	(47%)	$\boxed{26.6}$	(46%)
SMW2	$\boxed{54.0}$	(31%)	$\boxed{53.5}$	(25%)
Boarfish				
SMW1			3.6	(28%)
SMW2			12.1	-
European hake				
SMW1	$\boxed{1.4}$	(103%)	$\boxed{1.0}$	(104%)
SMW2	$\boxed{5.8}$	(66%)	$\boxed{5.3}$	(78%)
Chub mackerel				
SMW1	7.6	(115%)	3.3	(89%)
SMW2	22.9	-	21.5	-

4. Discussion

4.1. *Cod end selectivity*

The increase in cod end mesh size and change in mesh configuration from diamond to square mesh were found to positively affect the selectivity for all the species that were studied in the cod end selectivity experiments carried out for crustacean trawling (Papers I and II). Their influence was mainly on L_{50}, for all species except the Norway lobster, where a significant effect of mesh size was found only in SR (Table 7). The results suggest that the minimum cod end mesh size of 55 mm is too small for the catch of the shrimp species (rose shrimp and red shrimp) with a high fraction of undersized individuals retained. Increase in cod end mesh size from 55 to 70 mm without changing cod end design or twine material would contribute to reducing the catch of undersized shrimps, by placing their respective MLS's between the lengths at 25% and 50% retention.

Such an increase would reduce the amount of discards, particularly of undersized hake; of blue whiting, which accounted for approximately 50% of the total catch weight in these experiments; and of boarfish. Minor losses of larger individuals of Norway lobster above the current MLS are expected with this increase in mesh size. However, it should be noted that the MLS for this species (20 mm of carapace length) is inadequate, since it is well below the size of first maturation of 29 mm (C. Silva, pers. comm.). Furthermore, the commercial value for Norway lobster close to the MLS is low, and these individuals are often discarded. Horse mackerel is the only species for which the use of a larger mesh size would result in a significant escapement of commercial sized fish.

Data from fish trawling in the shallow assemblage off the south west coast (Paper III), where the selectivity could only be estimated using pooled data, also indicate that the current 65 mm mesh size is too small to respect the MLS for hake and axillary seabream. Horse mackerel was the only species for which this mesh size seems to be adequate. On the other hand, the increase in diamond mesh from 65 to 80 mm had a relatively small effect on the size selectivity for hake and horse mackerel, while the change in mesh configuration to 65 mm square mesh allowed for the escapement of a significant fraction of the catch of commercial sized fish. Comparison of these results, for hake and horse mackerel, with similar data in Paper IV, where the same species were captured in the deep groundfish assemblage, revealed the same scenario for hake, in diamond mesh cod ends, while larger horse mackerel captured were totally retained in these cod ends.

Possibly, the use of square mesh cod ends with mesh sizes smaller than 65 mm, or, alternatively, the use of diamond cod ends of higher mesh sizes or with a smaller number of meshes in circumference would situate the MLS's for these species between length at 25% and 50% retention.

Positive effects of cod end catch on selectivity were consistently observed either in L_{50} or in SR, for all species for which selectivity was studied based on individual haul analysis, with the exception of rose shrimp. It was the case of Norway lobster (Paper I), blue whiting (Paper II), and hake, blue whiting and horse mackerel (Paper IV). The results presented are in accordance with the hypothesis of an increase in selectivity at low catch levels, as found by O'Neil and Kynoch (1996) within a similar catch range.

The effect of cod end catch on selectivity may contribute to explaining the unexpected fact that the L_{50} estimated from individual haul analysis was observed to decrease for blue whiting (Paper IV), when cod end mesh size was increased from 70 to 80 mm, in spite of the small (but significant) positive effect of mesh size on L_{50} estimated in the selectivity model proposed for this species. In fact, total catch in the cod end was lower in four out of the six hauls analysed for the 80D cod end when compared with the 70D one. The same effect is most probably responsible for a similar decrease in L_{50} based on pooled data for hake in 80D when compared to 70D (Paper IV).

Unlike cod end catch effects, which have been extensively reported, the influence of towing depth on selectivity is herein reported for the first time. Positive influence of depth on L_{50} and SR is expressed in the selectivity models proposed for blue whiting and rose shrimp respectively, captured in crustacean fishing grounds off the south coast from 150 to 700 m. Data evidenced a length-dependence on depth, particularly for rose shrimp, with catches consisting almost exclusively of juveniles at lower depths from 150 to 200 m, where trawling should be avoided. Larger individuals and wider length class ranges were found at greater depths. The latter is probably responsible for the estimated effect of depth on SR (a 4.2 mm increase in SR for a correspondent increase of 100 m in depth). A similar effect on L_{50} was observed for blue whiting, although of much lower magnitude (L_{50} increasing 1.2 cm for each 100 m increase in depth) and significance. It is hypothesized that the observed increase in SR for the rose shrimp can to some extent reflect the wider length intervals recorded at greater depths from 200 to 400 m, while the increase in L_{50} for blue whiting can be related to more active escape behaviour of larger fish associated with greater swimming activity. However, care should be taken when trying to explain the effects of depth, as well as of cod end catch, on the selectivity parameters. The fact that these effects were estimated on L_{50} for blue whiting and the European hake (Papers II and IV), while for crustaceans (Paper I) such effects were found on SR, can also reflect the higher variability found in SR for crustaceans when compared to L_{50}, while for fish species the inverse was observed.

The effects of these variables were not directly addressed during these experiments; instead they emerged from the exploratory data analysis. They deserve further attention before definitive conclusions can be drawn. The effects of cod end catch, in particular, may become more evident when analysed within higher catch ranges on board commercial vessels. Furthermore, interaction between cod end catch and mesh size, not estimated in the models proposed, is likely to occur, and should be addressed within the scope of experiments specially designed to put in evidence such effects.

The selectivity parameters estimated for horse mackerel and hake when captured as target species (Paper III) were systematically lower than those obtained when the same species were captured as a by-catch (Paper II). While this was more evident for horse mackerel, for which these estimates could be obtained with a common mesh size (70D) in both experiments, for hake, both L_{50} and SR in 70 and 80 mm diamond cod ends (Paper III) did not differ much from those in 55 and 60 mm cod ends (Paper II). It is suggested that these differences in selectivity may be related to the distinct fish assemblages exploited, both in terms of the species captured and size composition of the individuals. On the other hand, differences in gear design between experiments could have affected the cod end geometry for the diamond mesh cod ends. The cod end perimeter was different between trawls, and differences in the cod end mesh opening, which were not controlled, probably occurred between experiments.

Differences in the experimental method, with unhooped covers in the fish trawl, could also possibly contribute to the lower selectivity estimates due to a masking effect. However, the analysis of selectivity data for the square mesh cod end in Paper III showed that both hake and axillary seabream escaped through meshes at a girth higher than mesh perimeter, which is not in accordance with such a hypothesis.

Also, for blue whiting the selectivity was higher when this species was captured in crustacean fishing grounds off the south coast (Paper II) compared to the south-west coast (Paper IV), for a common mesh size of 70mm. While the differences in size, with bigger individuals captured in the first case, can possibly contribute to explaining these results, the same considerations apply with regard to differences in the gear used.

Some differences can be noticed in the two models proposed for blue whiting when captured in crustacean (Paper II) and in fish trawling (Paper IV) with respect to the magnitude of the effects of mesh size on L_{50} (3.1 and 1.4 cm increase in L_{50} with 10 mm increase in mesh size respectively), indicating that, for this species, the impact of increasing mesh size on selectivity is higher for smaller mesh sizes.

A strong evidence is presented regarding the influence of fish shape on cod end selectivity. For round-bodied fish including hake and blue whiting, as well as fish with a more elliptical shape, such as the horse mackerel and the axillary seabream, escapement generally increased with increase in mesh size and particularly with the use of square mesh. On the other hand, the Norway lobster could take advantage of the higher mesh opening provided by the square mesh, but not of the increase in mesh size. The escape pattern for the four-spot megrim was totally different since escapement increased with mesh size in diamond cod ends, but decreased when mesh configuration was changed. There was however some evidence that the ability of fish to pass through cod end meshes does not entirely depend on the geometric relationship between fish body and mesh shape. In Paper III, where selectivity for the horse mackerel, the European hake and the axillary seabream was also expressed as a function of maximum body girth, the unexpected escapement of the two latter species, in the square mesh cod end, at girths higher than mesh perimeter suggests a more active escape behaviour compatible with higher swimming activity.

4.2. Evaluation of by-catch reduction devices

The use of BRD's greatly contributed to the exclusion of a substantial fraction of the non-commercial by-catch. The oblique sorting panel of 120 mm mesh size, associated with the 100 mm square mesh window (Paper V), was found to be the most effective by-catch reducer, without significant losses of crustaceans.

Escapement attained the highest rates for blue whiting and boarfish, particularly the former, for which good evidence of active escape behaviour was observed in all the combinations of BRD's tested, including the use of the square mesh window alone. For boarfish the exclusion from the trawl relied on previous guidance to the upper trawl level by the separator panel, as well as on the use of a square mesh window of higher mesh size. Data in Paper VI confirm these observations. Boarfish, unlike blue whiting, always escaped from the trawl in extremely low amounts, even when the square mesh window was placed at the top of the cod end.

Comparison of the data in Paper V with those in Paper VI for similar positions of the square mesh window on the upper belly evidenced lower escape rates in the latter. This clearly demonstrates that the effectiveness of similar windows depends on the trawl in which they are used. It is suggested that the better results achieved in Paper V were related to the more confined space in the trawl rear area due to a lower vertical opening, increasing the probability for the different fish species to contact the square mesh window, thus enhancing escapement. The results obtained in Paper VI suggest that exclusion for blue whiting would increase to a greater extent in top cod end windows placed in low-opening trawls. However, some loss of rose shrimp is expected, while for boarfish the escapement through windows placed at the top of the cod end will probably be always dependent on adequate stimuli, as was consistently observed throughout.

SF estimates in Paper V for horse mackerel and rose shrimp escaping through the 70 mm square mesh window used together with the 120 mm separator panel indicate lower selectivity when compared with previous estimates for the same species in 55 mm cod ends entirely made of square meshes (Papers I and II). Although good evidence was obtained that all fish reaching the trawl upper level encountered the window, the opportunity to escape was probably restricted due to the smaller area covered by the window, as well as its forward position in relation to the cod end, limiting the time that fish spend near the square meshes.

The experiments using separator panels and square mesh windows were based in small numbers of hauls with reduced catches, where high between-haul variability in exclusion was generally observed. Their effectiveness may become more evident with higher catches on board commercial vessels, particularly if escapement from the trawl increases with species catch size as it was suggested for boarfish (Paper V) and blue whiting (Paper VI). The panel complex design and installation are however pointed out as major drawbacks to its commercial acceptance, and it is not clear whether more effort should be put on the commercial testing of such options.

On the other hand, the utility of square mesh windows should be more closely examined, given their simple construction, low-cost and easy installation. Commercial testing of cod ends equipped with windows using other window designs placed in rear cod end areas is recommended. In fact, escapement through windows placed at the top of net panels, and particularly before the cod end, requires a good swimming ability to penetrate through the meshes (Briggs and Robertson, 1993) and the existence of visual stimuli (Glass et al., 1993). The relatively small size of the individuals captured in these experiments, together with low light levels associated to high depths, can possibly be on the basis of the poor results obtained, particularly for horse mackerel, for which there is experimental evidence regarding the effectiveness of square mesh windows (Briggs, 1992).

There is also a need for the estimation of selectivity parameters for these cod ends. An alternative to the use of top covers would be the estimation of the cod end selectivity by using a cover surrounding the whole cod end and window. This would allow for easier comparison of the selectivity in conventional and modified cod ends.

Until better alternatives are not developed, it is suggested that the increase in cod end mesh size to 70 mm, in crustacean trawls, would be a sensible option to avoid the catch of undersized shrimp and to reduce the huge amount of by-catch.

5. Final remarks

More recent studies on cod end selectivity were carried out by Fonseca et al. (2000) on board commercial crustacean and fish trawlers, at different seasons. Selectivity estimates in these studies support the idea that current mesh sizes retain a significant fraction of undersized individuals of most crustacean and fish commercial species. However, selectivity estimates representative of the entire fleet are still needed. The choice of optimal mesh sizes is another problem that deserves further attention in mixed demersal fisheries such as crustacean and fish trawling off the Portuguese coast. This choice is always a compromise (Stewart and Galbraith, 1989; Van Marlen, 1991), given the high number of species involved differing on their biological characteristics, as well as on their morphological traits.

Grid sorting systems were also recently tested as by-catch reduction devices on board research vessels, in crustacean fishing grounds (Fonseca et al., 2001, 2002, unpublished data). In these studies, and similarly to what was observed with increase in cod end mesh size, or the use of square meshes, a high proportion of the non-commercial by-catch could be excluded from the trawls, but always at the expenses of losing a fraction of target species and commercial by-catch. Information is still required on the use of these devices onboard commercial trawlers, as well as on the estimation of selectivity parameters.

The benefits to be gained in the long-term by increasing cod end mesh sizes or introducing other gear modifications need to be addressed. A central question to justify the adoption of gear modifications is that fish escaping through cod end meshes or other trawl areas survive and fully recover (Chopin and Arimoto, 1995). Survival rates estimated in North Atlantic fisheries for the Norway lobster, as well as for cod, haddock and whiting, were found to increase with increased mesh size, the use of square mesh cod ends, window cod ends and grid sorting systems. However, no studies were found for shrimps, hake or horse mackerel, that may justify the utility of such gear modifications in management programmes. The benefits to be gained by increasing cod end mesh sizes or introducing other gear modifications can be substantially smaller than expected if the survival rates of escapees are low, as demonstrated by Kuikka et al. (1996), in a study for the Baltic Sea herring. It was found that any benefit of increasing the cod end mesh size from 20 to 36 mm would require the survival of cod end escapees to increase to 80% from the current estimated level of about 15%.

It is believed that technical measures such as gear modifications can play an important role in management policies, particularly in crustacean trawl fisheries, given the magnitude of discards. However, they should not be separately considered from other measures such as the control of fishing effort. This is particularly important when the fishing pressure is high as it is the case in trawl fisheries off the Portuguese coast.

Finally, the importance of fisheries as a whole process should be considered in any fisheries management scheme (Hilborn and Walters, 1992; Charles, 2001). Attention has been mainly focused on biological issues when looking for regulation measures, with few attempts to study either the behaviour of the fishermen themselves, including fishing patterns, fishing effort and catch misreporting, and market behaviour, which can ultimately dictate the fishing activity.

These latter issues have been partially addressed in recent studies. Afonso-Dias et al. (2002) have recently developed a GIS tool to estimate and map fishing effort and landings for the crustacean fishing fleet, based on the Portuguese vessel monitoring system database, which continuously monitors geographic position of fishing vessels, and on landings database for this fleet. While the data available in this study are only for the period of 1998-99, extension of these data over a longer time series, as well as over a wider geographical area including the west coast, would allow a better understanding of the fleet dynamics. In particular, it would be extremely useful to investigate whether different *métiers* exist within fish trawlers (132 vessels) fishing along a coastal extension of 300 n.m. approximately, over different groundfish assemblages, or if opportunistic fishing takes place depending on the abundance or market value for a particular species or group of species. This would greatly simplify the complicated task of critically examining by-catch and discards in fish trawling, a fundamental step before technical measures, can be proposed in order to improve fisheries management.

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Size selectivity of diamond and square mesh cod ends for rose shrimp (*Parapenaeus longirostris*) and Norway lobster (*Nephrops norvegicus*) off the Portuguese south coast

Aida Campos[a,*], Paulo Fonseca[a], Karim Erzini[b,1]

[a]*IPIMAR, Avenida de Brasília, 1449-006 Lisbon, Portugal*
[b]*University of the Algarve, Centro de Ciências do Mar (CCMAR), Campus de Gambelas, 8000 Faro, Portugal*

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Abstract

The effects of an increase in cod end mesh size from 55 to 60 and 70 mm and a change of mesh configuration from diamond to square mesh on the size selectivity for rose shrimp *Parapenaeus longirostris* and Norway lobster *Nephrops norvegicus* captured off the Portuguese south coast were evaluated. The results were analysed taking into account between-haul variation in selectivity, and indicate a significant increase in L_{50} for rose shrimp with an increase in mesh size or with the use of a square mesh cod end, while for Norway lobster only mesh configuration was found to affect this parameter. Two other important external variables were identified; the trawling depth and the cod end catch, which influence between-haul variation, by increasing the selection range for rose shrimp and Norway lobster, respectively. The results obtained suggest that an increase in the current minimum mesh size of 55 mm would be advisable for rose shrimp in order to respect the minimum landing size of 24 mm carapace length presently established for this species. Moreover, trawling for rose shrimp should be avoided at depths above 200 m, in order to avoid catches consisting almost exclusively of juveniles. Such an increase in mesh size would have a minor impact in terms of losses of individuals above the minimum landing size for Norway lobster and would contribute to reducing the amount of discards in this fishery.

Keywords: Cod end selectivity; Mesh size; Mesh configuration; *Parapenaeus longirostris*; *Nephrops norvegicus*; Between-haul variation; L_{50}; SR

1. Introduction

The Norway lobster *Nephrops norvegicus* and the rose shrimp *Parapenaeus longirostris* are the two main target species in the trawl fishery for deep-sea crustacea off the Portuguese south coast (ICES Division IXa). Although the two species can be targeted separately since they have different depth distributions, they are captured together in a number of fishing grounds. At present a total of 25 fishing units are operating in this fishery using trawls with the minimum legal cod end mesh size of 55 mm.

As in many crustacean trawl fisheries world-wide, the number of by-catch species is high. Some of this by-catch is landed, comprising species such as the red shrimp, *Aristeus antennatus*, the horse mackerel

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[*] Corresponding author. Tel.: +351-21-302-7163; fax: +351-21-301-5948.
E-mail addresses: acampos@ipimar.pt (A. Campos), pfonseca@ipimar.pt (P. Fonseca), kerzini@ualg.pt (K. Erzini).

[1] Tel.: +351-289-800100; fax: +351-289-818353.

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Trachurus trachurus, the European hake *Merluccius merluccius* and the monkfishes *Lophius piscatorius* and *Lophius budegassa* that account for a significant part of the total value of the landings. However, most of the catch is of no or little commercial value and is discarded at sea. The blue whiting *Micromesistius poutassou*, the boarfish *Capros aper*, the conger eel *Conger conger* and many crustacean and cephalopod species are discarded. An average of 70% of the total catch in weight per haul was discarded in this fishery in 1995–1996 (Borges et al., 2001).

This fishery became important for Portuguese fishermen during the 1980s after fishing licenses ceased to be issued to Spanish vessels in 1983. In 1984 approximately 600 t of each species were landed and from 1984 to 1993, Norway lobster dominated the landings with between 300 and 600 t per year, while rose shrimp landings varied between 100 and 200 t. By this time the rose shrimp stock was considered to be overexploited (Pestana, 1991; Pestana and Ribeiro-Cascalho, 1991) and according to the ICES Working Group on *Nephrops* and *Pandalus* stocks (Anon., 1993) both male and female F levels were higher than F_{max}.

From 1994 until the present Norway lobster landings have decreased to between 100 and 200 t a year while those of rose shrimp have increased. According to the Working Group on *Nephrops* stocks (Anon., 1999) recruitment failure is believed to be one of the main reasons for the rapid decline in the stock of Norway lobster. As a consequence of the Norway lobster decline, there has been a shift of target species to the rose shrimp in recent years. Although there is scientific evidence of overexploitation for the rose shrimp stock (Mattos and Silva, 1995) the landings for rose shrimp have increased since 1994 due to good recruitment (Anon., 1999).

In 1991 the EC proposed an increase in the minimum cod end mesh size from 55 to 70 mm to become effective in January 1995 if no evidence of stock recovery was observed for Norway lobster. The use of more selective gears, among other management measures, has also been proposed by the ICES Working Group on *Nephrops* stocks in successive meetings, but never put in practice until the present.

An evaluation of the consequences of increasing the cod end mesh size was carried out by IPIMAR in 1993 (Study Contract 1992/11), with the study of the size selectivity of three different cod end mesh sizes (55, 60 and 70 mm) for the main commercial species in this fishery, both target and by-catch. Given strong evidence that mesh configuration is another cod end parameter that can significantly affect selectivity, the effect of using square mesh was also investigated for the 55 mm cod end.

A large amount of selectivity data was obtained for a number of species, including the target species and by-catch. In this study, results are presented for the two main target species; the rose shrimp and the Norway lobster.

2. Materials and methods

2.1. Data collection

Data were collected during two cruises of a total of 36 days at sea, carried out in 1993 off the south coast of Portugal on board the R/V “Noruega”, a 1500 HP stern trawler with a ramp belonging to IPIMAR. The first cruise was between March 20 and April 3, while the second took place between May 5 and May 25. A total of 133 valid hauls was carried out, during daylight hours and in stable weather and sea conditions, between Cabo de Sagres in the west (longitude 09°14′.5W) and Vila Real de S$^{\mathrm{to}}$ António (07°25′.7W) at depths from 152 to 706 m. Fishing areas and depths are shown in Fig. 1. The total number of hauls with each mesh size was 41, 33 35 and 24 for the 55, 60 and 70 diamond meshes and the 55 mm square mesh, respectively.

The gear used was a crustacean trawl of commercial design entirely made up of twisted polyethylene 60 mm mesh size, approximately 50 m long from the wing tips to the cod end joining row, with a circumference of 1064 meshes of 60 mm at the footrope level. Technical details are shown in Fig. 2. It was equipped with a 62.5 m length footrope made up of 18 mm combined rope covered with 16 mm polypropylene rope, weighted with 1.6 kg/m steel chain along the whole extension. Trawl rigging included 40 m sweeps and semi-oval otter boards of 650 kg each. Trawl geometry and speed over the bottom were recorded for most hauls using trawl depth, height and spread sensors, and a speed sensor. Vertical opening, wing end and door spread values remained virtually unchanged, at approximately 2.2, 33 and 94 m,

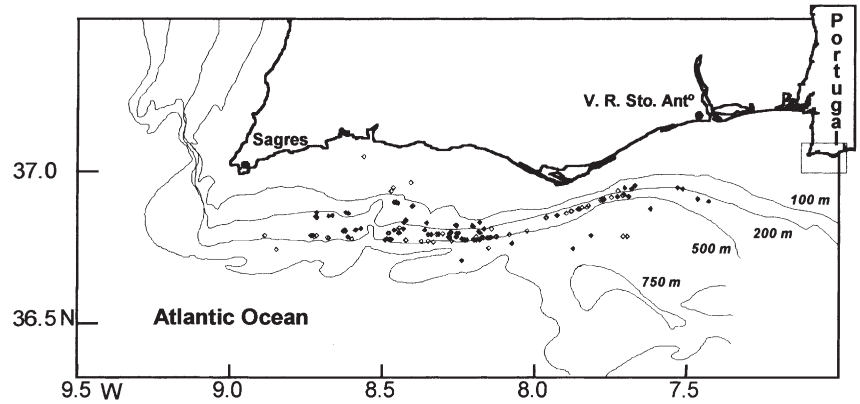


Fig. 1. Fishing areas and depths. Full and open marks correspond to hauls in first and second cruises, respectively.

respectively, at trawling speed, at 2.5 to 3.0 knots, the usual trawling speeds in this fishery. All hauls were carried out at a constant depth.

Commercial practices were followed with regard to the fishing grounds and the trawling speeds. However, tow duration was 1 h for all hauls, whereas in commercial fishing tows are usually at least 4 h long.

Four different mesh size/configuration cod ends were tested, with nominal values of 55, 60, and 70 mm for diamond mesh, and 55 mm for square mesh. All cod ends were made with 2.5 mm braided polyethylene as currently used in commercial trawls, except for the square mesh cod end where 2.0 mm braided twine was used. Cod end effective mesh sizes

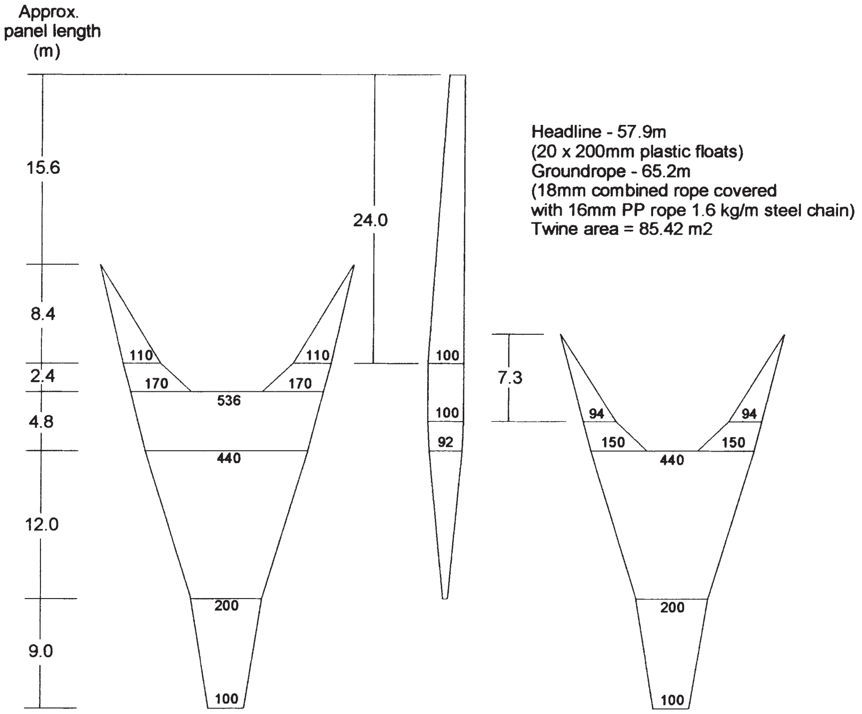


Fig. 2. Technical drawing for the trawl used.

Table 1
Details of cod ends (standard errors are in brackets)

	Nominal cod end mesh size (mm)			
	55D	60D	70D	55S
Measured	55.2 (0.96)	60.3 (1.34)	70.6 (1.27)	55.2 (0.92)
Number of measurements	115	182	102	161
Dimensions (number of meshes)				
Width	109	100	85	65[a]
Length	109	100	85	218[a]

[a] Number of bars.

were measured during the surveys as the inside stretched mesh size using a calliper due to the unavailability of the ICES gauge recommended by Pope et al. (1975). Cod end dimensions in number of meshes and effective mesh sizes are given in Table 1. The fully extended width of the diamond mesh cod ends was kept constant in order to achieve a similar mesh opening, since this has proved to be a variable which can affect selectivity significantly (Robertson and Ferro, 1988; Reeves et al., 1992; Galbraith et al., 1994). Although selection factors were calculated using the effective mesh size value, for practical purposes the nominal value is used throughout the text.

The experimental method used was the covered cod end (Pope et al., 1975). The cover was made of twisted PA 20 mm mesh size and 1.0 mm thick twine, with overall dimensions 1.5 times the width and the length of the cod ends (Fig. 3), as recommended by Stewart and Robertson (1985) for covers where large catches are not expected. Two hoops of approximately 2.2 m diameter made of galvanised iron were fitted inside the cover to minimise a possible masking effect of cod end meshes (Main and Sangster, 1991).

After hauling up, catches from cod end and cover were handled separately on board and weighed. All taxa were determined to the species level whenever possible. Carapace length and total length of the most important commercial crustacea and fish were measured to the millimetre and centimetre below, respectively.

For the Norway lobster the whole catch was measured in all hauls, while for the rose shrimp the greater numbers of individuals captured in the cod end and/or the cover necessitated random sub-sampling in an appreciable amount of hauls. The length class frequencies for each species in sub-sampled hauls were estimated by scaling up the measured frequencies in the sub-samples (cod end and cover) by the inverse of the sampling proportions.

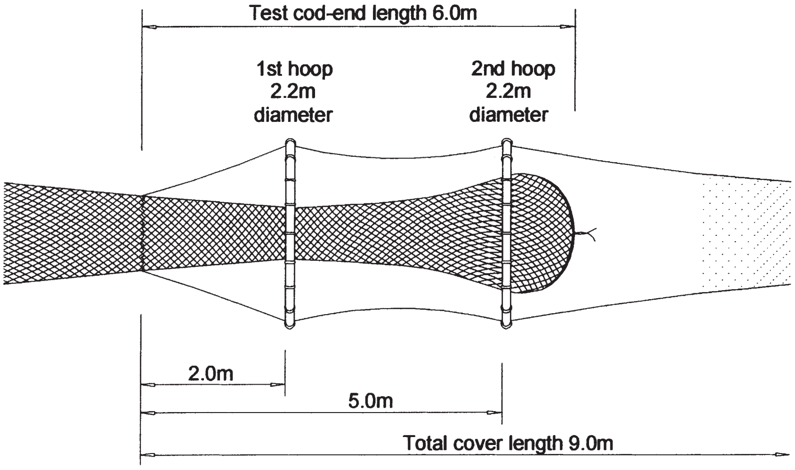


Fig. 3. Covered cod end and hoops.

2.2. Selectivity analysis

For each haul, the retention probability $r(l)$ in the cod end was modelled by means of the logistic selectivity curve

$$r(l) = \frac{\exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)}$$

where $r(l)$ is the probability that a fish of length l is retained, given that it entered the cod end, and $v = (\,v_1 \quad v_2\,)^T$ is the vector of selectivity parameters. The maximum likelihood estimator of v, $\hat{v}$, is approximately normally distributed with expected value v and variance matrix R (Fryer, 1991)

$$\hat{v} \sim N(v, R)$$

provided that a sufficient number of individuals exist in all length classes and retention values are from a large interval between 0 and 1. Estimation of v and R are described in Fryer (1991). Correction for the effects of sub-sampling was carried out according to Millar (1994) who showed that for sub-sampled hauls

$$r'(l) = \frac{q\exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)} = \frac{\exp(v'_1 + v_2 l)}{\exp(v'_1 + v_2 l)}$$

where $q = p_1/p_2$ is the ratio of sampling proportions in the cod end and cover, respectively. Therefore, the curve fitted to the retention proportions of raw data is also logistic, with parameters $v'_1 = v_1 + \ln(q)$ and v_2.

Wileman et al. (1996) recommend this approach in sub-sampled hauls data since the standard errors for the parameters can then be reliably estimated. However, it is considered that scaled data fits of a logistic curve provide similar estimates to those obtained with the raw data when q is close to unity and the same authors recommend that when sub-sampling, the ratio of the sampling fractions should be a value between 1/3 and 3.

The model of between-haul variation of Fryer (1991) was then used to investigate the between-haul variation of the selectivity parameters v_1 and v_2 by mesh size and mesh configuration, allowing the estimation of mean curves for the four different cod end meshes. Fryer assumes that the parameters $\hat{v}_i$, $i = 1, \ldots, H$ with H the number of hauls, are independent and multivariate normal

$$\hat{v}_i \sim N(\alpha, R_i + D)$$

with expected value $E\begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix}$ and variance matrix $R_i + D$, in which the variance matrices $\{R_i\}$ measure the within-haul variation and $\{D\}$ measures the between-haul variation in the selectivity parameters $\{\hat{v}_i\}$. This model was used to estimate D by residual maximum likelihood (Fryer, 1991), a method that gives better estimates for D when the number of hauls in each mesh size is low, as was the case in some situations in this study.

The model of Fryer was also used to model the selectivity data by estimating the individual contribution of some explanatory variables (the gear characteristics in study and other external variables that can play a role in between-haul variation) on the selectivity parameters estimated for these hauls. Under these conditions

$$\hat{v}_i \sim N(X_i\alpha, R_i + D)$$

where the expected value $E\begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = X_i\alpha, X_i$ being the design matrix of the q explanatory variables for haul i:

$$X_i = \begin{pmatrix} x_{i11} & x_{i12} & \cdots & x_{i1q} \\ x_{i21} & x_{i22} & \cdots & x_{i2q} \end{pmatrix}$$

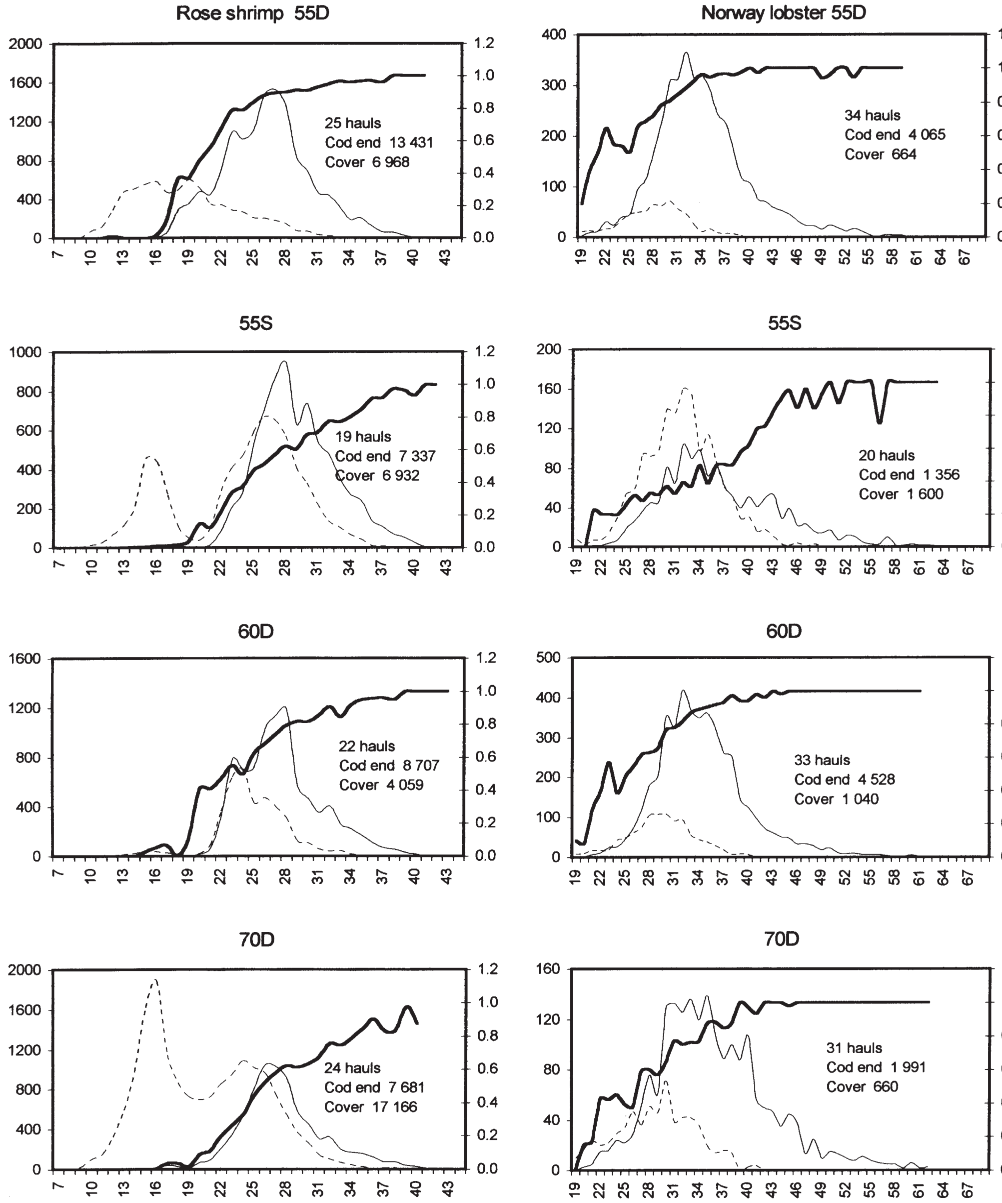
and $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_q)^T$ is the vector which determines the direction and magnitude of the influence of these variables on the selectivity parameters.

The selectivity parameters for individual hauls were estimated using an Excel spreadsheet (Tokai, 1997). This spreadsheet was modified by the authors to allow the estimation of v_i and R_i for sub-sampled hauls. Models which incorporate between-haul variation were adjusted using the software ECModeller (ConStat) which follows the methodology proposed by Fryer (1991).

3. Results

3.1. Summary of the data

The size structure of the catches in the different cod ends is presented in Fig. 4. Rose shrimp ranged in size between 10 and 40 mm carapace length and Norway lobster between 19 and 60 mm. The variation between mesh sizes in the numbers of individuals caught is related to differences in fishing effort


Rose shrimp 55D

25 hauls
Cod end 13 431
Cover 6 968

Norway lobster 55D

34 hauls
Cod end 4 065
Cover 664

55S

19 hauls
Cod end 7 337
Cover 6 932

55S

20 hauls
Cod end 1 356
Cover 1 600

60D

22 hauls
Cod end 8 707
Cover 4 059

60D

33 hauls
Cod end 4 528
Cover 1 040

70D

24 hauls
Cod end 7 681
Cover 17 166

70D

31 hauls
Cod end 1 991
Cover 660

Fig. 4. Size structure of the populations that entered the different cod ends: *X*-axis—carapace length (mm); *Y*-axis (left)—numbers; *Y*-axis (right)—percentage retained. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to percentage retained.

between cod ends. For rose shrimp, the fraction of the smaller length classes from 10 to 20 mm carapace length in the different cod ends reflects the number of hauls carried out at lower depths in the different situations, with three hauls at depths from 150 to 200 m for the 70 mm diamond mesh cod end while all tows with the 60D cod end took place at depths below 250 m.

As can be seen in Fig. 5, although there is some overlap, the depth distributions of the two species are different. Length dependence on depth can be observed, particularly for rose shrimp, for which large

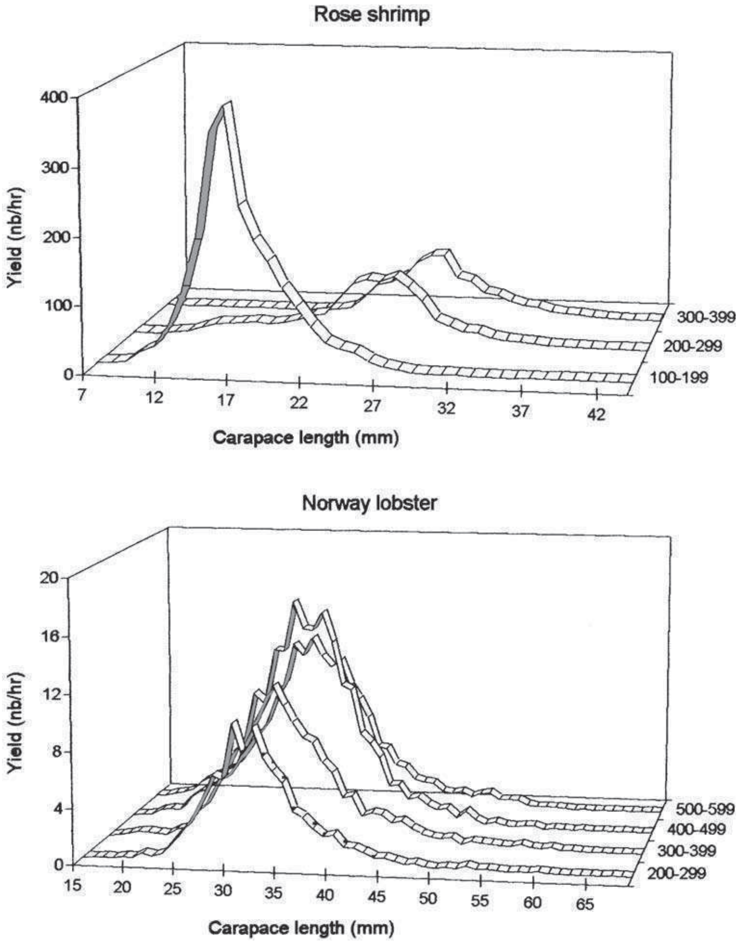


Fig. 5. Fishing yields in number of individuals per hour as a function of length class and depth for the rose shrimp and the Norway lobster.

numbers of juveniles were found between 150 and 200 m, while the adults were found between 200 and 400 m, together with the Norway lobster. The latter species was caught at depths to 600 m.

3.2. Selectivity analysis

A summary of hauls and catches is presented in Tables 2 and 3 for rose shrimp and Norway lobster, respectively. A total of 34 and 29 individual hauls were used in the analysis for rose shrimp and Norway lobster, respectively of which eight hauls could be analysed for both species.

The proportions (p) in Tables 2 and 3 of the number of individual hauls analysed to the number of hauls where more than 100 individuals were caught were low. These figures varied by cod end for both species, from 0.33 to 0.58 for rose shrimp and from 0.38 to 0.83 for the Norway lobster, with the lowest values of 0.33 and 0.38 corresponding to the 55D cod ends. Individual hauls were excluded either because of inadequate number of individuals or if the length interval was too narrow. For Norway lobster the main reason for excluding hauls was the high retention values observed for all mesh sizes (except in the 55 mm square mesh cod end), with few escapees, while for rose shrimp the retention pattern varied within the same cod end according to the length interval of individuals captured, and therefore hauls were excluded due to the lack of individuals in the cover,

Table 2
Summary of the hauls and catches for the different cod ends of rose shrimp

Haul number	Date	Hour start	Depth (m)	Length range (mm)	Cod end catch				Cover catch			
					Rose shrimp			Other (kg)	Rose shrimp			Other (kg)
					(kg)	Nb	Nb < MLS		(kg)	Nb	Nb < MLS	
55D												
08A	March 21	15:25	303	19–39	5.5	432	89	45	1.4	147	80	43
14A	March 22	17:25	175	11–30	1.7	201	93	232	1.5	290	254	27
16A	March 23	9:45	214	11–32	6.0	754	456	181	1.7	541	493	58
11B	May 07	8:15	207	11–32	22.5	2763	1677	330	6.6	1264	1198	120
14B	May 08	6:25	270	20–38	7.0	597	135	162	3.0	310	155	86
19B	May 09	6:45	199	11–33	3.2	435	303	633	5.6	1134	1086	304
83B	May 24	13:45	316	20–40	21.0	1248	24	75	2.8	231	20	7
n	7			11–40	66.8	6430	2777	1658	22.4	3917	3286	644
$N > 100$ ind.	21	$N = 25$		09–41	161.2	13431	3469	3908	37.2	6968	5707	1476
$p = n/N$	0.33				0.41	0.48			0.60	0.56		
55S												
50A	March 31	15:35	313	23–40	1.5	94	0	33	0.9	64	1	279
52A	April 01	10:15	330	22–38	3.4	229	4	55	2.8	222	13	367
53A	April 01	13:15	326	21–38	7.5	558	38	146	4.3	383	84	470
54A	April 01	15:35	297	18–39	6.5	505	46	30	5.0	432	122	110
55A	April 01	17:25	282	17–37	4.8	374	55	58	6.6	665	271	279
56A	April 02	7:40	308	20–38	4.3	357	39	40	3.1	322	81	527
57A	April 02	9:40	277	18–39	7.0	582	70	70	4.9	511	171	619
75B	May 23	6:30	330	22–41	18.5	1133	0	36	11.0	834	16	22
78B	May 23	13:50	362	23–40	26.0	1628	8	72	10.0	702	8	143
n	9			17–41	79.5	5460	260	540	48.5	4135	767	3121
$N > 100$ ind.	16	$N = 19$		08–42	106.6	7337	323	1578	66.3	6932	2614	4661
$p = n/N$	0.56				0.75	0.74			0.73	0.60		
60D												
20B	May 09	9:45	298	20–40	5.6	410	10	199	2.2	193	26	71
37B	May 14	7:15	258	18–37	6.5	532	90	142	3.7	370	143	80
38B	May 14	9:10	251	20–38	3.9	294	34	207	2.3	202	62	110
43B	May 15	8:35	333	20–41	17.5	1289	70	117	5.0	425	60	8
44B	May 15	10:25	301	20–41	24.0	2226	753	173	12.0	1347	672	106
45B	May 15	11:45	299	21–40	22.5	1637	186	291	10.0	766	108	340
46B	May 15	14:55	315	20–42	10.0	650	6	73	2.4	197	20	35
n	7			18–42	89.9	7038	1149	1202	37.5	3500	1091	2042
$N > 100$ ind.	13	$N = 22$		11–43	115.4	8707	1192	3519	43.1	4059	1297	1538
$p = n/N$	0.54				0.78	0.81			0.87	0.86		

Table 2 (*Continued*)

Haul number	Date	Hour start	Depth (m)	Length range (mm)	Cod end catch				Cover catch			
					Rose shrimp			Other (kg)	Rose shrimp			Other (kg)
					(kg)	Nb	Nb < MLS		(kg)	Nb	Nb < MLS	
70D												
18A	March 23	15:15	247	14–35	4.0	365	66	38	9.0	1252	660	45
20A	March 24	8:00	247	11–34	2.2	272	80	25	7.0	926	637	71
30A	March 26	13:15	258	19–39	2.4	182	14	28	3.1	297	122	62
34A	March 27	12:20	258	07–34	3.4	298	96	51	8.0	1132	788	51
36A	March 27	16:40	310	21–41	3.0	209	6	42	2.3	202	23	39
07B	May 06	8:40	296	19–39	4.5	353	59	82	3.2	327	143	99
58B	May 19	8:30	335	21–43	15.0	1042	28	74	11.0	886	62	39
59B	May 19	10:25	308	20–39	15.4	1200	121	82	9.5	798	132	59
60B	May 19	12:10	308	20–41	7.5	502	17	70	4.7	371	41	175
62B	May 20	6:45	325	22–44	11.0	337	3	55	5.0	344	3	10
63B	May 20	8:30	296	20–42	19.0	1518	84	108	11.0	946	160	262
n	11			07–44	87.4	6278	574	654	73.8	7481	2771	912
$N > 100$ ind.	19	$N = 24$		07–44	105.3	7684	804	2206	112.8	17166	11695	2248
$p = n/N$	0.58				0.83	0.82			0.65	0.44		

Table 3
Summary of the hauls and catches for the different cod ends of Norway lobster

Haul number	Date	Hour start	Depth (m)	Length range (mm)	Cod end catch				Cover catch			
					Norway lobster			Other (kg)	Norway lobster			Other (kg)
					(kg)	Nb	Nb < MLS		(kg)	Nb	Nb < MLS	
55D												
09A	March 21	17:35	368	22–54	5.1	173	0	108	0.6	41	0	36
39A	March 28	13:40	332	22–58	8.0	264	0	102	0.5	34	0	45
40A	March 29	15:40	335	16–56	8.0	286	0	96	1.2	77	1	29
12B	May 07	11:50	566	16–58	33.0	1150	4	193	5.0	273	7	4
18B	May 08	15:50	453	16–48	2.9	91	0	176	0.9	53	4	7
n	5			16–58	57.0	1964	4	675	8.1	478	12	121
$N > 100$ ind.	13		$N = 34$	16–68	125.0	4065	11	3945	10.8	664	25	1503
$p = n/N$	0.38				0.46	0.48			0.75	0.72		
55S												
44A	March 30	12:30	348	26–56	2.4	52	0	33	1.9	73	0	96
49A	March 31	13:40	332	20–56	1.7	40	0	30	2.5	105	0	343
52A	April 01	10:15	330	20–38	1.6	80	0	57	3.1	170	0	367
53A	April 01	13:15	326	18–44	2.3	113	0	151	2.6	159	2	472
58A	April 02	12:30	435	18–52	7.0	222	0	90	5.0	218	5	48
59A	April 02	14:35	500	20–54	2.7	69	0	54	1.7	82	0	14
24B	May 10	9:10	345	16–52	3.2	90	0	50	3.1	122	5	132
75B	May 23	6:30	330	28–60	9.0	161	0	45	2.9	77	0	30
78B	May 23	13:50	362	28–62	10.0	197	0	88	3.4	100	0	150
79B	May 23	15:45	304	26–60	4.8	92	0	63	1.4	44	0	136
n	10			16–62	44.6	1116	0	662	27.6	1150	12	1789
$N > 100$ ind.	12		$N = 20$	16–62	52.9	1356	0	1632	37.7	1600	14	4690
$p = n/N$	0.83				0.84	0.82			0.73	0.72		
60D												
20B	May 09	9:45	298	20–44	16.0	714	0	188	2.9	163	0	70
29B	May 12	11:40	435	18–52	12.0	371	0	109	1.5	69	1	15
30B	May 12	13:45	480	16–56	30.0	943	0	162	6.0	306	7	19
31B	May 12	16:00	461	22–56	7.0	186	0	68	0.6	32	0	7
34B	May 13	10:55	341	18–44	5.5	221	0	146	3.1	177	2	162
35B	May 13	13:10	324	16–50	10.0	408	0	77	1.0	66	3	35
50B	May 16	11:20	513	18–50	11.0	389	0	41	0.4	35	5	3
n	7			16–56	91.5	3232	0	791	15.5	848	18	312
$N > 100$ ind.	10		$N = 33$	16–60	149.3	4528	2	3485	18.9	1040	21	1562
$p = n/N$	0.70				0.61	0.71			0.82	0.82		

Table 3 (*Continued*)

Haul number	Date	Hour start	Depth (m)	Length range (mm)	Cod end catch				Cover catch			
					Norway lobster			Other (kg)	Norway lobster			Other (kg)
					(kg)	Nb	Nb < MLS		(kg)	Nb	Nb < MLS	
70D												
35A	March 27	14:20	361	16–44	4.0	176	2	16	0.8	70	17	3
05B	May 05	16:25	540	16–54	9.0	264	1	13	2.5	159	15	8
07B	May 06	8:40	296	20–44	2.0	74	0	85	0.9	57	0	102
62B	May 20	6:45	325	26–62	6.5	109	0	59	0.6	20	0	14
63B	May 20	8:30	296	22–60	7.0	129	0	120	0.7	23	0	272
65B	May 20	14:15	490	20–56	3.5	113	0	38	0.6	39	0	7
72B	May 22	11:15	542	20–52	3.6	118	0	72	0.4	34	0	4
n	7			16–62	35.6	983	3	404	6.4	402	32	410
$N > 100$ ind.	10		$N = 31$	16–62	73.5	1991	0	2238	9.8	660	32	2351
$p = n/N$	0.70				0.48	0.49			0.66	0.61		

if larger shrimp were caught or inversely, due to low retention values with almost total escapement, whenever the catch consisted largely of smaller individuals.

The low numbers of hauls included in the individual haul analysis shows that the option of taking into account between-haul variation necessarily implies the loss of information from a significant number of hauls. Therefore it was decided to simultaneously estimate mean curves based on pooled data from all hauls and to compare the selectivity parameters obtained by both methods.

The catches for both species in all individual hauls are only a small fraction of the total catch, with low numbers of Norway lobster caught in the cod end and the cover in particular. In the hauls analysed for rose shrimp (Table 2) the by-catch was essentially composed of boarfish at depths to 300 m and of blue whiting at greater depths, while for Norway lobster (Table 3) the bulk of the by-catch consisted of blue whiting.

The results of the selectivity parameters estimation are given in Tables 4 and 5. The estimated parameters v_1 and v_2 of the fitted logistic curves adjusted are shown for all individual hauls and mean curves (according to Fryer (1991), and based on pooled data), together with the respective variance–covariance matrix R_i which estimates within-haul variation in the parameters. The larger values of R_i estimated for Norway lobster in many of the hauls indicate large within-haul variability and reflect the low numbers of individuals in those hauls in the cod end and/or in the cover. Despite the similar values estimated for the selectivity parameters in the mean curves, the variance estimates given by R_i are in general higher for the mean curves according to Fryer. Between-haul variation given by the matrix D is high for both species in the 55D cod end and for rose shrimp in the 70D cod end as well, reflecting the higher variability associated to the different hauls within these mesh sizes, which can be noticed for instance in terms of haul depth and length interval of the individuals captured.

For practical purposes, the selectivity curve is described not in terms of v_1 and v_2, but of the selectivity parameters L_{50}, the length of 50% retention, and SR, the selection range, defined as $\mathrm{SR} = L_{75} - L_{25}$. Both these estimates and their respective 95% confidence intervals are presented along with the sampling proportions in the cod end and cover for all rose shrimp hauls.

The two species were differently selected by the four cod ends in study, as can be seen in the estimates for L_{50} and SR in Tables 4 and 5. For rose shrimp, the L_{50} estimated taking into account between-haul variation increases with a correspondent increase in mesh size from 21.8 to 24.0 and 27.1 mm and with a change in mesh configuration to 27.1 mm. The same pattern can be observed for the 95% confidence intervals (20.5–23.1, 22.8–24.9 and 26.2–27.7 mm for the diamond mesh cod ends and 26.2–27.9 mm for the 55 mm square mesh cod end).

For Norway lobster, the values estimated for L_{50} in the diamond cod ends vary between 25.8 and 28.1 mm, while in the 55 mm square mesh cod end the estimated value was 34.7 mm, which shows the higher selective properties of the 55 mm square mesh. The confidence intervals for this parameter in the diamond mesh cod ends are 25.9–28.2, 23.9–28.1 and 26.6–29.8 mm in the 55, 60 and 70D, respectively, showing a high degree of overlap, while in the 55S cod end the confidence interval was 33.1–36.4 mm.

With respect to SR, the estimated values for Norway lobster show an increase from 6.1 (4.7–7.5) to 8.0 (6.8–9.2) and 9.4 mm (8.0–10.8) in the diamond mesh cod ends, while this estimate is much higher in the 55 mm square mesh cod end (16.0 mm, with a confidence interval of 13.4–18.6). For rose shrimp, SR estimates are very similar in all cod ends, between 8.9 and 9.3 mm, except in the 55D where this estimate was found to be substantially lower (5.7 mm). Confidence intervals are 4.5–6.9, 8.6–10.0, 7.7–10.8 and 6.7–11.1 mm for the 55D, 55S, 60D and 70D, respectively.

L_{50} and SR estimates for the mean curves in this study (according to Fryer (1991), and based on pooled data) show a good agreement when comparing similar cod ends except for the Norway lobster in the 55D cod end. In this case, the L_{50} estimate of 27.1 mm is much higher than that estimated for pooled data (23.0 mm), and even higher than the same estimate for the 60D cod end (25.8 mm). Inversely, the estimated SR of 6.1 is low when compared to the same estimate for pooled data (9.6).

Individual haul and mean curves are shown in Fig. 6. High variability within the same cod end in the position and shape of the individual curves can be observed for both species, suggesting the influence of variables other than mesh size and mesh configuration on the selectivity parameters estimated for these species.

Table 4
Selectivity estimates for rose shrimp (in brackets are 95% CI for L_{50} and SR)

Haul number	L_{50}	SR	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}	Sampling proportions	
								Cod end	Cover
55D									
08A	22.4 (21.5–23.3)	6.3 (4.5–8.0)	−7.847	0.350	1.329	−0.0533	0.00216	1.00	1.00
14A	22.8 (22.4–23.2)	4.5 (3.8–5.2)	−11.091	0.487	0.649	−0.0284	0.00126	1.00	1.00
16A	20.7 (20.3–21.2)	4.1 (3.4–4.8)	−11.089	0.535	0.933	−0.0427	0.00198	1.00	1.00
11B	19.3 (18.9–19.7)	5.1 (4.4–5.9)	−8.269	0.428	0.402	−0.0192	0.00093	0.33	0.50
14B	23.4 (22.9–23.9)	6.6 (5.5–7.8)	−7.792	0.333	0.474	−0.0188	0.00075	1.00	1.00
19B	23.2 (22.6–23.8)	5.6 (4.6–6.5)	−9.122	0.394	0.446	−0.0214	0.00104	1.00	0.50
83B	20.0 (17.2–22.8)	11.5 (8.0–15.1)	−3.811	0.191	0.651	−0.0227	0.00080	0.50	1.00
Mean curve (Fryer)	21.8 (20.5–23.1)	5.7 (4.5–6.9)	−8.393	0.386	0.862	−0.0379	0.00179		
Mean curve (pooled)	20.8 (20.2–21.4)	6.1 (5.2–6.9)	−7.524	0.362	0.328	−0.0144	0.00065		
D					5.359	−0.2370	0.01129		
55S									
50A	28.1 (26.5–29.8)	8.6 (3.8–13.3)	−7.229	0.257	3.802	−0.1282	0.00436	1.00	1.00
52A	28.1 (27.5–28.7)	10.1 (7.9–12.3)	−6.142	0.218	0.403	−0.0142	0.00051	1.00	1.00
53A	25.4 (24.5–26.3)	9.6 (7.2–12.0)	−5.809	0.229	0.529	−0.0192	0.00070	0.32	1.00
54A	25.9 (25.0–26.8)	10.4 (6.9–13.9)	−5.475	0.211	0.815	−0.0309	0.00118	1.00	0.50
55A	28.2 (27.3–29.1)	8.6 (6.5–10.7)	−7.201	0.255	0.603	−0.0229	0.00088	1.00	1.00
56A	26.5 (25.7–27.3)	8.6 (6.3–10.9)	−6.738	0.254	0.742	−0.0275	0.00103	1.00	1.00
57A	26.0 (25.5–26.5)	8.7 (7.1–10.4)	−6.552	0.252	0.366	−0.0138	0.00052	1.00	1.00
75B	28.7 (28.1–29.4)	8.5 (6.8–10.3)	−7.392	0.257	0.540	−0.0179	0.00060	0.30	0.50
78B	26.3 (25.1–27.6)	9.9 (7.1–12.6)	−5.861	0.223	0.772	−0.0256	0.00085	0.25	0.50
Mean curve (Fryer)	27.1 (26.2–27.9)	9.3 (8.6–10.0)	−6.405	0.237	0.085	−0.0026	0.00009		
Mean curve (pooled)	26.5 (26.1–27.0)	8.7 (7.7–9.8)	−6.672	0.251	0.156	−0.0057	0.00021		
D					0.154	−0.0016	0.00002		
60D									
20B	25.6 (24.6–26.5)	6.6 (4.6–8.7)	−8.498	0.333	1.796	−0.0650	0.00237	1.00	1.00
37B	24.8 (24.3–25.3)	8.5 (7.0–10.1)	−6.392	0.258	0.344	−0.0131	0.00050	1.00	1.00
38B	25.2 (24.4–26.0)	7.9 (5.6–10.2)	−6.997	0.278	0.982	−0.0370	0.00140	1.00	1.00
43B	21.8 (20.4–23.3)	12.7 (10.0–15.4)	−3.767	0.173	0.239	−0.0085	0.00031	1.00	1.00
44B	23.1 (22.5–23.7)	9.0 (7.0–10.9)	−5.656	0.245	0.403	−0.0162	0.00065	0.33	0.33
45B	23.0 (20.8–25.3)	11.2 (5.6–16.7)	−4.533	0.197	1.546	−0.0574	0.00215	0.31	0.50
46B	23.3 (21.3–25.4)	9.6 (6.1–13.2)	−5.320	0.228	1.266	−0.0445	0.00158	0.50	1.00
Mean curve (Fryer)	24.0 (22.8–24.9)	9.3 (7.7–10.8)	−5.690	0.237	0.360	−0.0121	0.00041		
Mean curve (pooled)	22.9 (22.5–23.4)	9.3 (8.3–10.4)	−5.399	0.236	0.111	−0.0043	0.00017		
D					1.842	−0.0600	0.00196		
70D									
18A	27.3 (26.8–27.9)	4.6 (3.7–5.5)	−13.031	0.476	1.331	−0.0524	0.00208	1.00	1.00
20A	27.1 (25.7–28.5)	6.4 (4.0–8.8)	−9.358	0.345	2.316	−0.0950	0.00393	1.00	1.00
30A	28.1 (27.5–28.8)	6.4 (5.1–7.6)	−9.709	0.345	0.776	−0.0286	0.00107	1.00	1.00
34A	27.8 (26.9–28.7)	6.4 (5.1–7.7)	−9.502	0.342	0.663	−0.0269	0.00110	1.00	0.50
36A	28.4 (27.4–29.4)	9.6 (6.4–12.8)	−6.501	0.229	1.062	−0.0371	0.00131	1.00	1.00
07B	26.0 (25.3–26.7)	8.3 (6.2–10.4)	−6.899	0.265	0.681	−0.0258	0.00099	1.00	1.00
58B	27.5 (26.9–28.1)	14.1 (11.3–17.0)	−4.271	0.155	0.180	−0.0063	0.00022	0.50	0.50
59B	24.4 (22.7–26.1)	15.2 (8.6–21.8)	−3.531	0.145	0.659	−0.0241	0.00089	0.58	0.58
60B	26.8 (26.3–27.4)	10.7 (8.8–12.7)	−5.491	0.205	0.249	−0.0088	0.00032	1.00	1.00
62B	25.6 (23.6–27.6)	15.0 (9.6–20.5)	−3.739	0.146	0.595	−0.0195	0.00065	0.50	1.00
63B	24.3 (22.8–25.7)	14.8 (9.5–20.1)	−3.597	0.148	0.480	−0.0175	0.00064	0.50	0.50
Mean curve (Fryer)	27.1 (26.2–27.7)	8.9 (6.7–11.1)	−6.674	0.246	0.817	−0.0282	0.00098		
Mean curve (pooled)	26.8 (26.3–27.3)	7.0 (6.1–7.9)	−8.432	0.315	0.256	0.0099	0.00039		
D					8.334	−0.2859	0.00985		

Table 5
Selectivity estimates for Norway lobster (in brackets are 95% CI for L_{50} and SR)

Haul number	L_{50}	SR	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}
55D							
09A	27.6 (27.1–28.0)	4.6 (4.0–5.2)	−13.176	0.478	0.662	−0.0223	0.00076
39A	26.6 (25.1–28.0)	5.0 (3.3–6.6)	−11.759	0.443	4.388	−0.1454	0.00486
40A	26.3 (25.5–27.1)	6.7 (5.5–8.0)	−8.614	0.328	0.728	−0.0246	0.00084
12B	25.9 (25.1–26.7)	8.3 (7.2–9.5)	−6.809	0.263	0.300	−0.0098	0.00032
18B	29.3 (28.4–30.1)	7.0 (5.5–8.4)	−9.242	0.316	0.859	−0.0278	0.00091
Mean curve (Fryer)	27.1 (25.9–28.2)	6.1 (4.7–7.5)	−9.766	0.360	1.464	−0.0508	0.00181
Mean curve (pooled)	23.0 (22.0–24.1)	9.6 (8.3–10.9)	−5.266	0.229	0.186	−0.0062	0.00021
D					6.179	−0.2159	0.00776
55S							
44A	37.6 (33.4–41.8)	14.1 (3.1–25.1)	−5.852	0.156	3.867	−0.1082	0.00308
49A	40.1 (35.4–44.8)	12.8 (4.6–21.1)	−6.859	0.171	3.163	−0.0894	0.00258
52A	37.5 (30.8–44.2)	22.8 (4.5–41.0)	−3.620	0.097	1.016	−0.0336	0.00112
53A	34.1 (28.6–39.6)	28.7 (1.9–55.5)	−2.614	0.077	0.974	−0.0322	0.00108
58A	32.8 (31.5–34.2)	14.0 (9.9–18.1)	−5.161	0.157	0.519	−0.0155	0.00047
59A	34.4 (32.0–36.9)	15.4 (8.5–22.2)	−4.923	0.143	0.997	−0.0294	0.00089
24B	36.7 (33.8–39.7)	16.4 (6.7–26.1)	−4.929	0.134	1.691	−0.0482	0.00140
75B	34.0 (30.9–37.2)	15.4 (8.0–22.8)	−4.855	0.143	1.531	−0.0393	0.00103
78B	31.9 (28.7–35.2)	18.2 (9.6–26.8)	−3.854	0.121	0.992	−0.0265	0.00072
79B	33.2 (31.4–35.0)	11.3 (7.4–15.1)	−6.475	0.195	1.271	−0.0348	0.00097
Mean curve (Fryer)	34.7 (33.1–36.4)	16.0 (13.4–18.6)	−4.774	0.137	0.160	−0.0043	0.00013
Mean curve (pooled)	35.2 (34.3–36.1)	16.1 (13.4–18.7)	−4.806	0.137	0.138	−0.0040	0.00012
D					0.408	−0.0093	0.00028
60D							
20B	23.8 (21.7–25.9)	9.7 (6.7–12.8)	−5.365	0.225	0.916	−0.0306	0.00103
29B	25.2 (21.2–29.2)	10.8 (5.5–16.0)	−5.145	0.204	2.245	−0.0682	0.00211
30B	28.2 (27.5–28.9)	9.1 (7.9–10.3)	−6.796	0.241	0.230	−0.0071	0.00022
31B	27.5 (26.0–29.0)	6.6 (4.7–8.5)	−9.141	0.332	2.034	−0.0642	0.00205
34B	30.3 (29.4–31.2)	8.1 (5.9–10.4)	−8.174	0.270	1.095	−0.0350	0.00113
35B	23.7 (21.8–25.5)	7.6 (5.4–9.9)	−6.800	0.287	1.344	0.0461	0.00161
50B	22.9 (21.7–24.0)	5.8 (4.7–6.9)	−8.660	0.379	0.899	−0.0329	0.00123
Mean curve (Fryer)	25.8 (23.9–28.1)	8.0 (6.8–9.2)	−7.083	0.274	0.234	−0.0083	0.00042
Mean curve (pooled)	25.2 (24.7–25.8)	9.7 (9.0–10.5)	−5.710	0.226	0.066	−0.0021	0.00007
D					0.638	−0.0253	0.00184
70D							
35A	25.1 (23.6–26.6)	8.0 (5.6–10.5)	−6.842	0.273	1.131	−0.0397	0.00143
05B	28.7 (27.9–29.6)	9.2 (7.6–10.7)	−6.898	0.240	0.354	−0.0114	0.00038
07B	30.1 (28.0–32.2)	10.6 (4.6–16.6)	−6.241	0.208	2.824	−0.0897	0.00289
62B	29.0 (23.9–34.0)	14.3 (8.1–20.6)	−4.437	0.153	1.574	−0.0396	0.00101
63B	28.7 (23.9–33.4)	10.7 (4.3–17.0)	−5.910	0.206	4.251	−0.1184	0.00334
65B	27.4 (26.0–28.8)	8.2 (5.7–10.7)	−7.347	0.268	1.346	−0.0437	0.00144
72B	27.7 (25.7–29.8)	7.5 (4.6–10.4)	−8.133	0.293	2.795	−0.0891	0.00289
Mean curve (Fryer)	28.1 (26.6–29.8)	9.4 (8.0–10.8)	−6.550	0.233	0.190	−0.0072	0.00032
Mean curve (pooled)	26.7 (26.0–27.4)	10.3 (9.0–11.5)	−5.711	0.214	0.145	−0.0046	0.00015
D					0.236	−0.0162	0.00111

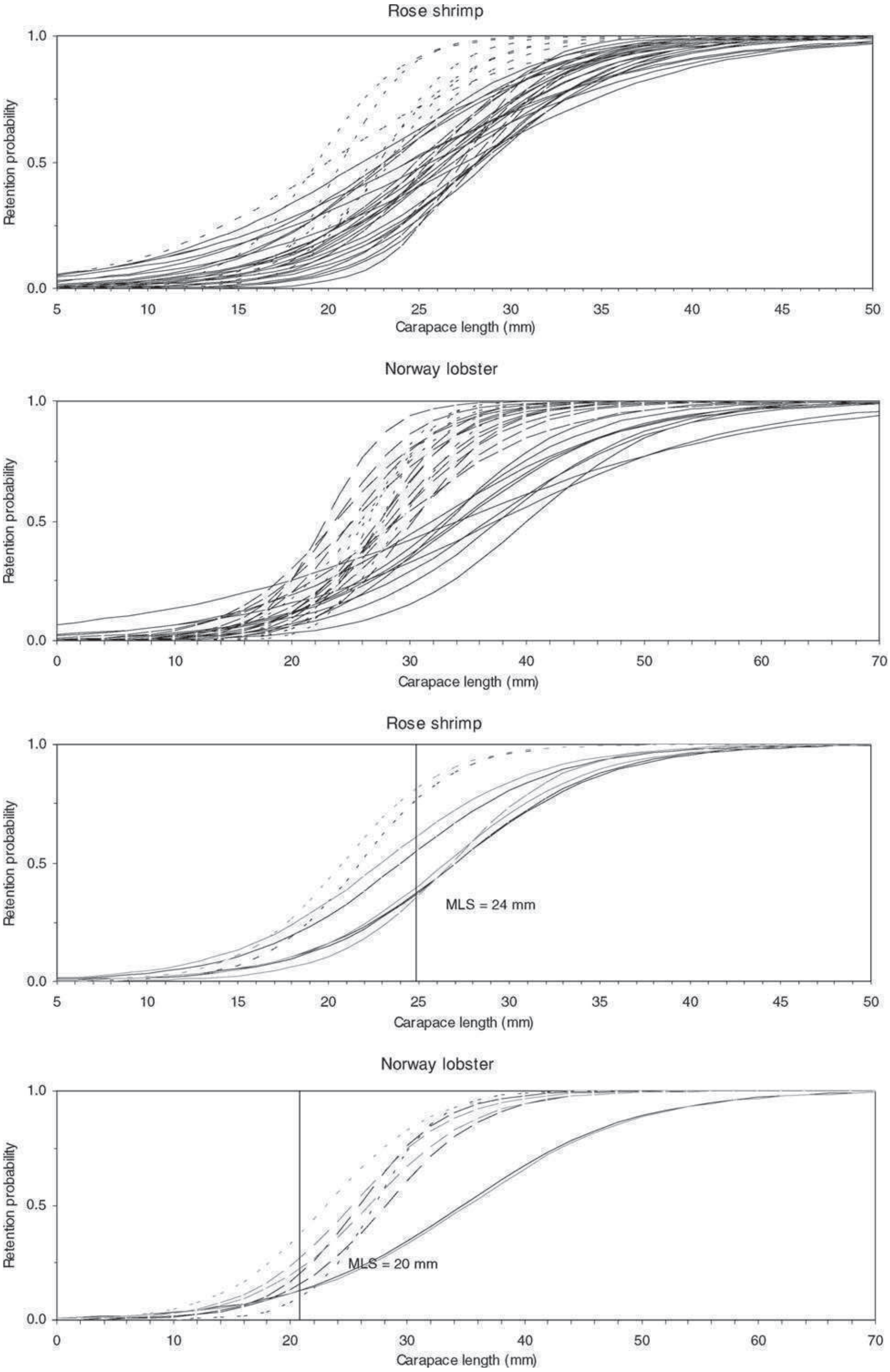


Fig. 6. Selectivity curves for rose shrimp and Norway lobster in the four cod ends for individual hauls and mean curves. Black lines correspond to mean curves according to Fryer and grey lines to mean curves based on pooled data. (- - -) 55D; (– – –) 60D; (— — —) 70D; (— - —) 55S.

A number of external variables which are expected to explain part of the observed between-haul variation in the selectivity parameters L_{50} and SR were recorded during these experiments. In a preliminary analysis the correlation between each of these variables and the selectivity parameters was estimated. Since cod end catch has been found to affect selectivity by conditioning on the escapement through cod end meshes (Suuronen et al., 1991; Madsen and Moth-Poulsen, 1994; O'Neill and Kynoch, 1996; Madsen et al., 1998) the effects of this variable on L_{50} and SR were investigated. The effects of depth were also investigated given that size frequency distributions and species composition are depth dependent. In addition, the variable cruise and various diversity indices were also investigated as possible explanatory variables.

Of all these external variables, only depth was found to play a significant role in between-haul variation for rose shrimp by positively affecting SR ($r^2 = 0.483$). For Norway lobster, a value of 0.348 was calculated for r^2 between SR and total catch weight (but not cod end catch weight) and a positive correlation was found between L_{50} and SR ($r^2 = 0.45$).

Fryer's model (Fryer, 1991) was employed to investigate the between-haul variation of the logistic parameters, v_1 and v_2, as well as the selectivity parameters L_{50} and SR, and their dependence on the explanatory variables mesh size, m_i, mesh configuration, t_i, depth, d_i, total catch, C_i and cod end catch, c_i. All were adjusted as continuous variables except for mesh configuration, which was adjusted as a factor with two levels. A high number of all possible linear expressions of these parameters as functions of these four variables were tested for the rose shrimp and the Norway lobster.

The best models, based on the lowest value for Akaike's information criterion (AIC), defined to be AIC = ($-2 \times$ log-likelihood $+ 2 \times$ number of parameters) (Fryer and Shepherd, 1993), are

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_2 m_i + \alpha_3 t_i \\ \alpha_1 + \alpha_4 d_i \end{pmatrix}$$

for the rose shrimp

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_3 t_i \\ \alpha_2 + \alpha_4 t_i + \alpha_5 m_i + \alpha_6 c_i \end{pmatrix}$$

for the Norway lobster

Table 6
Parameter estimates for the species in study along with the respective standard errors and *t*-value

Parameter	Estimate	Standard error	*t*-value
Rose shrimp			
α_1 (constant)	−3.54273	1.51	−2.3
α_2 (mesh size)	0.38952	4.06×10^{-3}	95.9
α_3 (mesh configuration)	5.40141	0.47	11.4
α_4 (depth)	0.04154	5.41×10^{-3}	7.7
Norway lobster			
α_1 (constant)	27.21343	0.52	52.7
α_2 (constant)	−16.49389	3.47	−4.8
α_3 (mesh configuration)	7.40264	0.93	8.0
α_4 (mesh configuration)	9.0248	1.09	8.2
α_5 (mesh size)	0.34809	5.19×10^{-2}	6.7
α_6 (cod end catch)	0.02426	4.70×10^{-3}	5.2

The estimated alpha parameters are given for both species in Table 6 along with their standard errors and *t*-values, which give an idea of the relative importance of all variables in the model. Apart from the cod end variables mesh size and mesh configuration that affected L_{50} for rose shrimp, SR for this species was positively affected by trawling depth. For Norway lobster, L_{50} was affected only by mesh configuration, while SR increased with mesh size and mesh configuration and there was a small but significant effect of cod end catch on SR.

4. Discussion

The data analysed in this study are from two different cruises. However, differences in selectivity due to cruise are not expected to be significant since the vessel, the gear and type of rigging, the experimental method and the way the hauls were carried were constant. Furthermore, the time interval between cruises did not coincide with major changes in the life cycle, for example with regard to spawning, of either species. For the rose shrimp, two spawning periods are reported, one in June–August and the other in October–December (Ribeiro-Cascalho and Arrobas, 1987; Ribeiro-Cascalho, 1988) while for the Norway lobster an extended spawning period from August to March has been reported (Lopes de Castro, 1988).

Despite the low catches recorded, average fishing yields in kg h^{-1} from all individual hauls observed for the commercial 55D cod end were of 9.5 and 11.4 kg h^{-1} for rose shrimp and Norway lobster, respectively. These figures exceed those reported 1 year after these experiments by Cadima et al. (unpublished data) for seven units in this fishery for rose shrimp (around 6.0 kg h^{-1}) but are lower to the fishing yields of 13.3 kg h^{-1} obtained with the same mesh size in selectivity trials on board the commercial vessel "Porto Bravo" in May 1999 (Fonseca et al., unpublished data). For Norway lobster, the value of 11.4 kg h^{-1} obtained in this study is well above that of 1.3 kg h^{-1} recorded during the latter experiments.

This is the first study in south European waters in which a selectivity analysis was carried out using the individual haul approach. However, as referred to above, the proportion of individual hauls which was analysed was low for both species. This was because in a typical haul these species were poorly represented in terms of numbers of individuals both in the cod end and the cover. For the Norway lobster the retention was high in all cod ends except for the 55S. Sardà et al. (1993) and Mytilineou et al. (1998) reported similar experiments for Norway lobster in the Mediterranean with cod ends from 38 to 60 and 32 to 53 mm, respectively, where an individual haul approach was not possible. For rose shrimp, the reasons for having excluded a high number of hauls vary with the length interval of individuals captured, which in turn was found to be dependent on depth.

Previous selectivity studies in Portuguese waters were based exclusively on pooled data. The value for L_{50} of 21.8 mm estimated for rose shrimp in the 55D cod end is lower than the value of 24.6 mm obtained in 1983 in the same waters by Ribeiro-Cascalho (1988) using a polyethylene cod end of the same nominal mesh size. The SR of 8.8 mm obtained by this author was greater than our estimate of 5.7 mm. For Norway lobster selectivity data in the same waters with 55D cod ends were obtained by Figueiredo and Castro (1983) and Figueiredo (1984, 1985). These authors estimated values for L_{50} between 21.6 and 29.0 mm, while SR values ranged from 11.3 to 14.0 mm, well above the values found in the present study. More recent data (October 1998) from experiments on commercial vessels using 55 and 70 mm diamond cod ends (Fonseca et al., unpublished data) resulted in L_{50} values of 22.0 and 28.6 mm for rose shrimp and 25.9 and 28.9 mm for Norway lobster. SR values were found to be 13.3 for both rose shrimp and Norway lobster with the 55D cod end, while for the 70D cod end they were 9.8 and 10.2. L_{50} values are within the range of those found in this study, while those for SR are higher for the 55D cod end.

Of all these authors, only Fonseca et al. provide a detailed description of the gear used. However, a number of differences between trawls concerning their size, footrope type and cod end materials used (polyamide vs. polyethylene) could be noticed, which are likely to be responsible for part of the observed variability in the results. Differences in the structure of the populations and in fish condition related to time at which experiments took place can also explain differences between selectivity parameters given by other authors and those found in this study.

The selectivity models obtained for the two species are very different from each other. While for rose shrimp the selectivity increased with an increase in mesh size and change in mesh configuration from 55 mm diamond to 55 mm square mesh, for the Norway lobster the 55 mm square mesh cod was clearly more size selective compared to the diamond mesh cod ends. In addition, length dependency on depth was much more evident for rose shrimp, with depth found to be an important external variable conditioning selectivity, while for Norway lobster significant effects of depth on selectivity could not be detected. These differences may be largely due to the morphology of the two species and in part to the fact that only a small number of hauls (eight hauls, corresponding to a fraction of 15% of all hauls) could be analysed for both species. The relationship between depth and SR is shown for rose shrimp in Fig. 7. An increase in SR with depth can be observed in all cod ends at depths

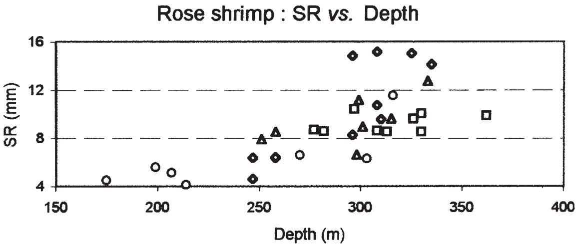


Fig. 7. Selection range (SR) values for rose shrimp plotted against fishing depth for all cod ends tested. Circles, triangles and lozenges correspond to 55, 60 and 70 mm diamond cod ends, respectively and squares to the 55 mm square mesh cod end.

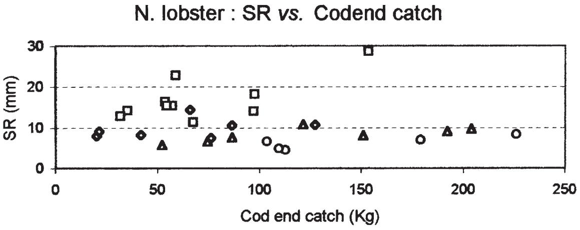


Fig. 8. Selection range (SR) values for Norway lobster plotted against cod end catch size for all cod ends tested. Circles, triangles and lozenges correspond to 55, 60 and 70 mm diamond cod ends, respectively and squares to the 55 mm square mesh cod end.

from approximately 250 to 350 m, the depth interval covering the usual fishing depths for rose shrimp and where both species were fished together.

The relationship between SR and cod end catch for Norway lobster (Fig. 8) is much less evident. A mesh effect on SR independent of the catch size can be seen, with higher values of SR associated with larger mesh sizes or with the use of the square mesh cod end. Furthermore, the range of common catch values is very low since higher cod end catches are associated with the lower mesh sizes, while in the 70D and the 55S cod ends most of the catch escaped through cod end meshes. However, a slight increase in SR in all cod ends with increasing catch size was found.

The literature concerning the effects of variables other than mesh size and mesh configuration on the selectivity of crustacean species is limited. The only reference found for the Norway lobster was in Briggs (1986) citing the work of Charuau (1979), in which the selection factor for this species was found to increase with increasing cod end catch.

Evidence of the effects of cod end catch on selectivity parameters (particularly L_{50}) is however discussed in a number of studies for fish species such as herring, haddock and whiting, but the results obtained by the different authors are somewhat controversial. Suuronen et al. (1991) report a significant reduction in L_{50} for herring with cod end catches up to 1600 kg. A similar trend was found for whiting by Madsen and Moth-Poulsen (1994) and by Madsen et al. (1998) for Baltic sea cod with cod ends fitted with a square mesh window, at catch ranges from 200 to 600 kg and 300 to 800 kg, respectively. Different results were reported by O'Neill and Kynoch (1996) for haddock and whiting. These authors found an increase in L_{50} with catch size for small catches from approximately 100 to 400 kg for both species and they suggest that this tendency may not continue with increasing catch size, with the L_{50} levelling out or decreasing after a certain catch level. Of all these studies, only Madsen and Moth-Poulsen (1994) and Madsen et al. (1998) reported a clear variation in selection range with catch. But while in the first study a reduction in SR is reported with increasing cod end catch, in the second a positive effect of catch on SR was found.

The effects of cod end catch on L_{50} have been explained by O'Neill and Kynoch (1996) in terms of the correspondent alteration to the cod end geometry and degree of mesh opening. As the catch builds up the meshes in front of the cod end open wider and selectivity increases, up to a point where the maximum mesh opening is achieved and any further increase in catch size has no effect on selectivity. The effect of cod end catch on SR for Norway lobster found in this study could possibly be viewed within the scope of a similar mechanism (initial increase of SR when the meshes are more open at the front of the cod end and further decrease), in spite of the fact that swimming and escape abilities are much lower for the Norway lobster than for the previously mentioned species.

Cod end catches for Norway lobster hauls recorded in this study ranged from 20 to 226 kg and are well below the usual figures in the commercial fishery, where the average haul duration is at least 4 h. It is expected that with more commercial sized catches, the effect of this variable on selectivity may become more evident and this can be subject to further investigation analysing cod end selectivity data from commercial hauls. There is clearly a need for more data and analysis before definitive conclusions on the effects of cod end catch on selectivity parameters can be drawn, especially when crustacean species are the targets. Furthermore, it should be noted that these effects must be analysed taking into account the fact that catch is itself dependent upon cod end selectivity and therefore interaction effects can occur between this variable and other variables that affect cod end selectivity.

The predicted values for L_{50} and SR are plotted against the observed values for rose shrimp and Norway lobster in Fig. 9. Although the relationships observed are significant, a large amount of variability could not be explained, particularly with regard to L_{50}

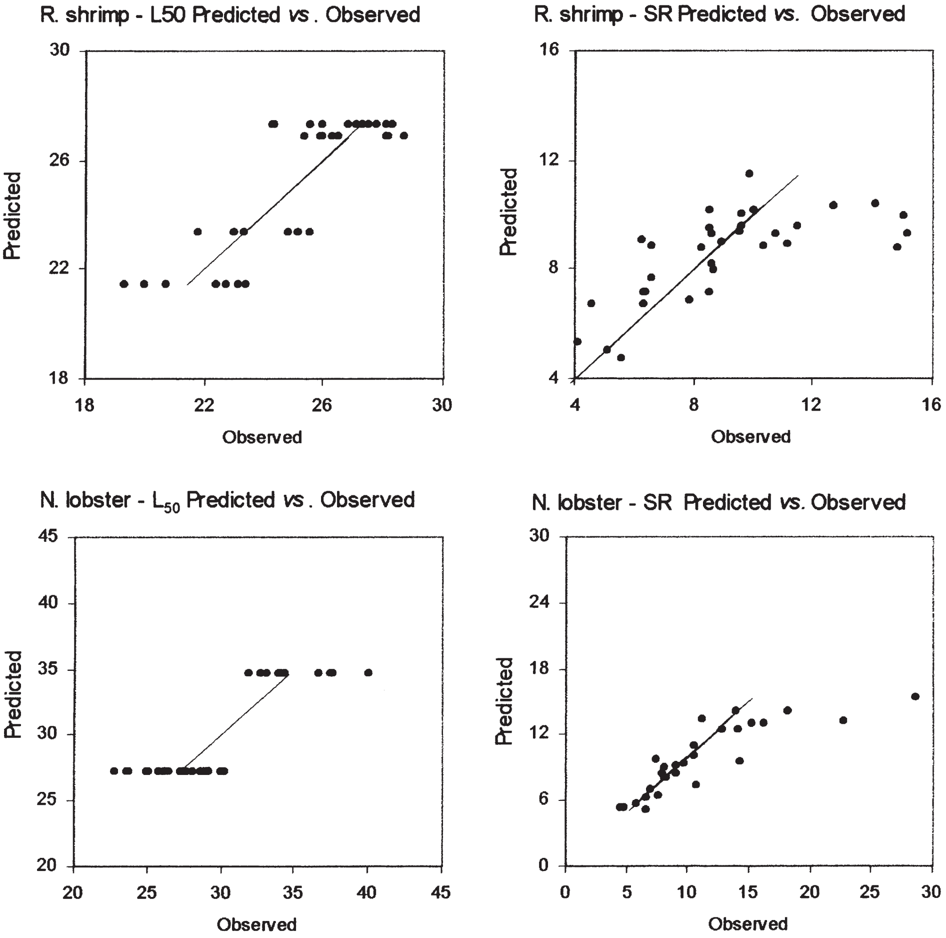


Fig. 9. Predicted values for the selectivity parameters L_{50} and SR plotted against observed values for rose shrimp and Norway lobster.

for Norway lobster. Neither could the higher values for SR in some of the hauls, both for the rose shrimp and the Norway lobster, be explained. Uncontrolled differences in environmental and/or gear conditions probably contributed to the variability observed.

This study has shown that for rose shrimp the 55 mm diamond mesh size is not appropriate for an MLS of 24 mm, with retention of approximately 70% of under-sized individuals, while the use of larger mesh sizes (60 and 70 mm diamond or 55 mm square mesh) lowered this value to 50 and 30%, respectively. Furthermore, trawling at lower depths from 150 to 200 m resulted in catches consisting almost exclusively of juveniles. In the case of Norway lobster, the retention of individuals below the MLS of 20 mm of carapace length was between 10 and 15% when the diamond mesh cod ends were used. However, it must be noted that very few individuals below 20 mm were captured and as selectivity is likely to change with the size range of individuals it is difficult to predict what would be the results if the catches were composed of a higher proportion of smaller individuals.

These results suggest that in the case of rose shrimp an increase in mesh size to 60 or even 70 mm would be advisable in order to respect the MLS of 24 mm for this species. According to the data obtained in this study the resulting losses in the capture of Norway lobster would be minor. A change in mesh configuration would on the other hand have no significant impact in selectivity for rose shrimp, but would increase the length at 50% retention to a value near 35 mm of carapace length for Norway lobster. The use of a larger mesh size or a change to a square mesh configuration would contribute to reducing the amount of blue whiting, boarfish and under-sized (<27 cm) European hake discards in this fishery (Ferreira et al., unpublished data). The only commercial species captured in significant quantities for which an increase in mesh size would significantly reduce the catch of legal-sized individuals is the horse mackerel, for which the present legal mesh size of 55 mm is appropriate for the MLS of 15 cm (Ferreira et al., unpublished data).

5. Concluding remarks

The emphasis of the experimental design in this study was the determination of the effects of cod end mesh size on size selectivity. The effects of mesh configuration were also investigated but to a lesser extent, since only the 55 mm square mesh cod end was tested. All the considerations made here apply only to the range of mesh sizes tested and to the change in mesh configuration from 55 mm diamond to 55 mm square mesh. They also apply to particular characteristics of cod ends tested (dimensions, material and twine diameter) and to only one season of the year, spring.

The effects of both depth, for rose shrimp, and cod end catch size, for Norway lobster deserve further attention, particularly the latter which should be investigated within the range of catch rates on board commercial vessels.

Finally, the implementation of technical measures such as the cod end mesh size or mesh configuration should be based not only on the results of selectivity trials such as the ones carried out in this study but also on the knowledge of survival of escaping crustaceans. There is no existing information on post-escapement survival of either species in Portuguese waters.

Acknowledgements

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Size selectivity of diamond and square mesh cod ends for four by-catch species in the crustacean fishery off the Portuguese south coast

Aida Campos[a,*], Paulo Fonseca[a], Karim Erzini[b,1]

[a] *IPIMAR, Avenida de Brasília, 1449-006 Lisbon, Portugal*

[b] *University of the Algarve, Centro de Ciências do Mar (CCMAR), Campus de Gambelas, 8000 Faro, Portugal*

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Abstract

The effects of an increase in cod end mesh size from 55 to 60 and 70 mm and a change of mesh configuration from 55 mm diamond to 55 mm square mesh on the size selectivity of four by-catch species (the red shrimp *Aristeus antennatus*, the European hake *Merluccius merluccius*, the horse mackerel *Trachurus trachurus* and the blue whiting *Micromesistius poutassou*) commonly captured in the crustacean fishery off the Portuguese south coast, were evaluated. Selectivity parameters for blue whiting, the most abundant species in the catches, were estimated taking into account between-haul variation, while for the remaining species, captured in much lower quantities, the selectivity estimates were based on pooled data by length class for all hauls within the same cod end. Length at 50% retention, L_{50}, was found to increase with mesh size and with the change in mesh configuration for all the studied species. For blue whiting trawling depth and cod end catch were found to play a role in between-haul variation by increasing L_{50} as well. The results suggest that an increase in the current minimum mesh size of 55–70 mm would be advisable to be compatible with the minimum landing sizes (MLSs) of 29 mm carapace length and 27 cm total length for red shrimp and hake, respectively, while it would greatly reduce the amount of discards, particularly those for blue whiting, that accounted for approximately 50% of the total catch weight. Horse mackerel was the only species for which the use of a larger mesh size would result in a significant escapement of individuals above the MLS of 15 cm.

Keywords: Cod end selectivity; By-catch; Mesh size; Mesh configuration; *Aristeus antennatus*; *Merluccius merluccius*; *Trachurus trachurus*; *Micromesistius poutassou*; Between-haul variation; L_{50}; SR

1. Introduction

A total of about 30 fishing vessels, mostly targeting the rose shrimp *Parapenaeus longirostris* and the Norway lobster *Nephrops norvegicus*, operate in the Portuguese trawl fishery for deep-sea crustacea off the south coast, using a cod end mesh size of 55 mm. As in many crustacean trawl fisheries throughout the world and depending on the fishing grounds, fishing depths and time of the year, by-catch species are captured in quantities that can greatly exceed those of the target species. Some of this by-catch, comprising species such as the European hake *Merluccius*

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[*] Corresponding author. Tel.: +351-21-302-7163; fax: +351-21-301-5948.
E-mail addresses: acampos@ipimar.pt (A. Campos), pfonseca@ipimar.pt (P. Fonseca), kerzini@ualg.pt (K. Erzini).

[1] Tel.: +351-289-800100; fax: +351-289-818353.

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merluccius, the horse mackerel *Trachurus trachurus*, the red shrimp *Aristeus antennatus* and a vast number of other species such as the monkfishes *Lophius* spp. and several species of cephalopods is landed above the respective minimum landing sizes (MLSs) (data from the General Directorate for Fisheries and Aquaculture, database).

An average of 70% of the total catch in weight per haul was discarded in this fishery in 1995–1996 (Borges et al., 2001). A significant proportion of the discards includes the blue whiting *Micromesistius poutassou*, the boarfish *Capros aper* and many other species of little or no commercial value. In addition, a certain proportion, not quantified, corresponds to undersized individuals of commercial species (e.g. hake, horse mackerel, cephalopods) that form the basis of other fisheries in these waters.

The present EU legislation (Regulation no. 850/98) stipulates that shrimp must make up at least 30% of the catch when cod end mesh sizes in the range of 55–59 mm are used, while targeting Norway lobster implies the use of a 70 mm mesh size.

Selectivity data were presented for the two main target species in this fishery, the rose shrimp and the Norway lobster by Campos et al. (2002). In the present study, cod end selectivity was studied for the most important by-catch species. Although of no commercial value, blue whiting was the most abundant species in the catches and was included in the analysis along with red shrimp, horse mackerel and European hake which are commercially valuable by-catch species.

2. Materials and methods

2.1. Data collection

The data were collected during two cruises, carried out in 1993 off the south coast of Portugal on the R/V "Noruega", a stern trawler with ramp belonging to the Portuguese Institute for Fisheries and Sea Research (IPIMAR). The first cruise was carried out between 20 March and 3 April, and the second between 5 and 25 May. The hauls were carried out between Cabo de Sagres in the west and Vila Real de Sto António in the east, on commercial fishing grounds at depths from 152 to 706 m (Fig. 1). Altogether, 133 valid hauls with duration of 1 h were carried out using diamond mesh cod ends of nominal mesh sizes of 55 mm (41 hauls), 60 mm (33 hauls) and 70 mm (35 hauls) and a square mesh cod end of 55 mm mesh size (24 hauls).

A crustacean trawl of commercial design was used, made up of twisted polyethylene 60 mm mesh size, about 50 m long from the wing tips to the cod end joining row, with a circumference of 1064 meshes at the footrope level (Fig. 2). It was equipped with a 62.5 m length footrope made up of 18 mm combination rope covered with 16 mm polypropylene, weighed with a 1.6 kg/m steel chain along the whole extension. Trawl geometry and water speed were recorded for most of the hauls using Scanmar depth, height and spread sensors, and a speed sensor. Vertical opening for this trawl was around 2.2 m with wing end and door spread values of 33 and 94 m, respectively, at normal commercial trawling speeds from 2.5 to 3.0 knots. The trawl

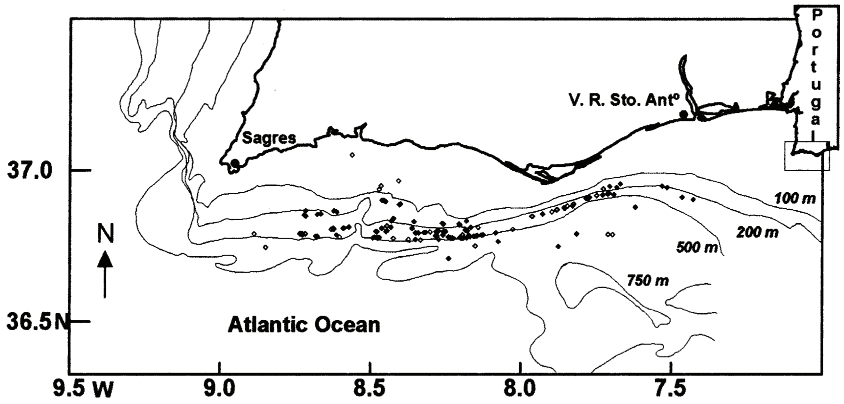
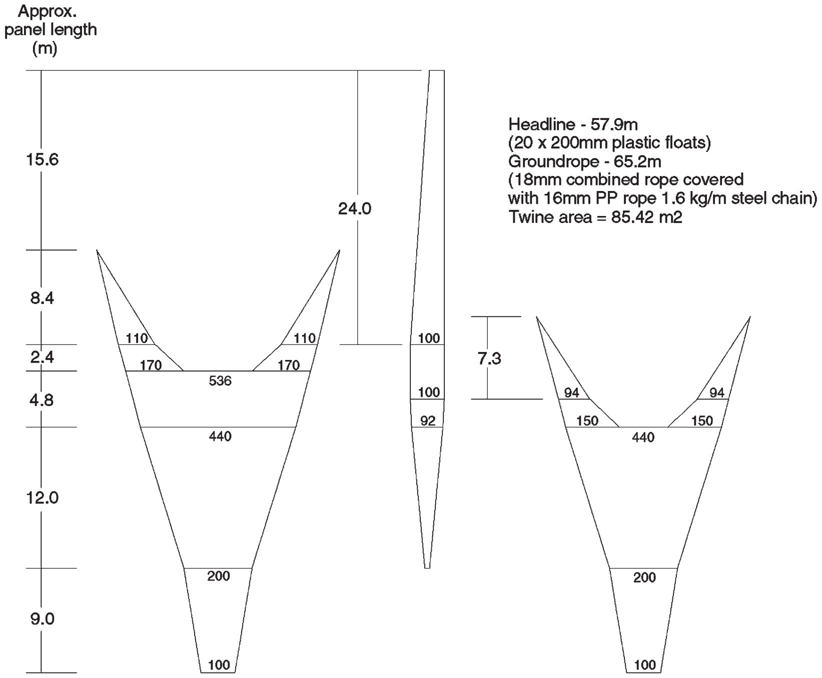


Fig. 1. Fishing areas and depths. Full and open marks correspond to hauls in first and second cruise, respectively.



Headline - 57.9m
(20 x 200mm plastic floats)
Groundrope - 65.2m
(18mm combined rope covered
with 16mm PP rope 1.6 kg/m steel chain)
Twine area = 85.42 m2

Fig. 2. Technical drawing for the trawl used.

rigging used included 40 m sweeps and semi-oval otterboards weighing 650 kg each.

Cod end dimensions in number of meshes and effective mesh sizes are given in Table 1. All cod ends were made up of 2.5 mm single braided polyethylene, except for the square mesh cod end where 2.0 mm twine was used. The fully extended width of the diamond mesh cod ends was kept constant in order to achieve a similar mesh opening in all cod ends, since this is a variable that can significantly affect selectivity (Robertson and Ferro, 1988; Reeves et al., 1992; Galbraith et al., 1994). Cod end effective mesh sizes were measured during the surveys as the inside stretched mesh size using a calliper. The selection factors were calculated using the effective mesh size values. However, for practical reasons, their nominal value will be referred to throughout the text.

The experimental method used was the hooped covered cod end, described in Main and Sangster (1991) and Wileman et al. (1996). Two hoops of approximately 2.2 m diameter made of stainless steel were

Table 1
Details of cod ends. Standard errors are in brackets

Nominal	Cod end mesh size (mm)			
	55D	60D	70D	55S
Measured	55.2 (0.96)	60.3 (1.34)	70.6 (1.27)	55.2 (0.92)
Number of measurements	115	182	102	161
Dimensions (number of meshes)				
Width	109	100	85	65[a]
Length	109	100	85	218[a]

[a] Number of bars.

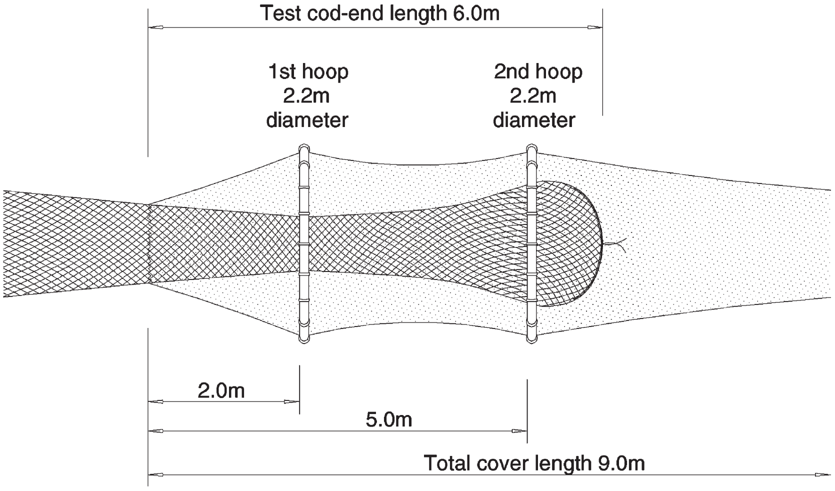


Fig. 3. Covered cod end and hoops.

fixed inside the cover to prevent a possible masking effect of cod end meshes (Fig. 3). The cover was made of single twisted PA 20 mm mesh size and 1.0 mm twine thickness, with overall dimensions 1.5 times the width and length of the cod ends, as proposed by Stewart and Robertson (1985) for covers where large catches are not expected.

After hauling up, catches from both trawl cod end and cover were handled separately on board and weighed. All taxa were identified to the species level whenever possible and the respective weights registered both in the cod end and the cover. Carapace length (CL, mm) for crustacea and total length (TL, cm) for fish were measured to the unit below.

The whole catch was measured in all hauls for red shrimp and hake, while random samples were taken of horse mackerel and blue whiting, captured in large numbers in many of the hauls. The length class frequencies were then estimated by scaling up the sub-sampled frequencies by the ratio of the total weight to the sub-sample weight.

2.2. Selectivity analysis

The probability $r(l)$ that a fish of length l is retained, given that it entered the cod end, was modelled by means of the logistic curve:

$$r(l) = \exp\frac{v_1 + v_2 l}{1 + \exp(v_1 + v_2 l)}$$

where $\hat{v} = (v_1, v_2)^{\mathrm{T}}$ is the maximum likelihood estimator of the vector of selectivity parameters. Estimation of $\hat{v}$ and the respective variance matrix R are described in Fryer (1991).

For all the species except blue whiting $\hat{v}$ was estimated based on pooled data, summing up the numbers of individuals for each length class across all hauls within the same cod end. For blue whiting it was possible to estimate selectivity by haul, and mean selectivity curves were fitted for all four cod ends taking into account between-haul variation of the selectivity parameters v_1 and v_2. The variances of the selectivity parameters for this model are given by $R_i + D$, where the matrix R_i measures within-haul variation, while the matrix D measures between-haul variation in the parameters. D was estimated by residual maximum likelihood (Fryer, 1991), since in some situations the number of hauls of each mesh size was low. Correction for the effects of sub-sampling was carried out for all individual hauls following Millar (1994).

Fryer's (1991) model was also employed in a subsequent phase to model the selectivity data for blue whiting by estimating the individual contribution of some explanatory variables, such as the gear characteristics and other external variables that can play a role in the between-haul variation of the estimated selectivity parameters. Under these conditions:

$$\hat{v}_i = \begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = X_i \alpha$$

where X_i is the design matrix of the q explanatory variables for haul i

$$X_i = \begin{pmatrix} x_{i11} & x_{i12} & \cdots & x_{i1q} \\ x_{i21} & x_{i22} & \cdots & x_{i2q} \end{pmatrix}$$

and $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_q)^{\mathrm{T}}$ is the vector which determines the direction and magnitude of the influence of these variables on the selectivity parameters.

The selectivity parameters for individual hauls were estimated using an Excel spreadsheet (Tokai, 1997). This spreadsheet was modified by the authors in order to allow the estimation of v and R for sub-sampled hauls. Models incorporating between-haul variation were fitted using the ECModeller (ConStat, DK) software which implements the methodology proposed by Fryer (1991). The between-haul variation of $L_{50} = (-v_{i1}/v_{i2})$ and $\mathrm{SR} = (2\ln(3)/v_{i2})$ was investigated, allowing the expression of the selectivity models in terms of L_{50} and SR instead of v_1 and v_2. A large number of all possible linear expressions of the selectivity parameters as functions of the explanatory variables: mesh size (m_i), mesh configuration (t_i), trawling depth (d_i), cod end catch (c_i) and cruise (C_i) were tested. Mesh size, depth and cod end catch were modelled as continuous variables, while mesh configuration and cruise were included as two-level factors. The choice of the model which best describes the data was based on the lowest value for Akaike's Information Criterion—AIC (Fryer and Shepherd, 1996).

3. Results

3.1. Summary of the data

Altogether 122 taxa, including crustaceans (28), fish (80) and cephalopods (6) belonging to 66 families were recorded in the experimental fishing trials. Blue whiting was the most abundant species, accounting for 48% of the total biomass that entered all cod ends (Fig. 4), followed by the boarfish (15%), while the main commercial by-catch fish species were horse mackerel, hake and the anglerfish *Lophius budegassa*. Rose shrimp and the Norway lobster accounted for only 3 and 2%, respectively, of the total biomass of the catches.

3.2. Blue whiting (*M. poutassou*)

Most of the individuals were from 19 to 35 cm in length in all cod ends except the 60D, where the length class range was from 21 to 35 cm (Fig. 5). They were caught at depths ranging from 175 to 706 m. All length frequency distributions were unimodal, with the mode at 22 cm, for the 55D and 55S cod ends, and unimodal at 26 cm for the 60D cod end. The length frequency distribution of the individuals caught in the 70D cod end was bimodal with a minor peak at 22 cm and a major one at 27 cm.

The number of individuals captured was much greater in the 55S cod end than in the others, in spite

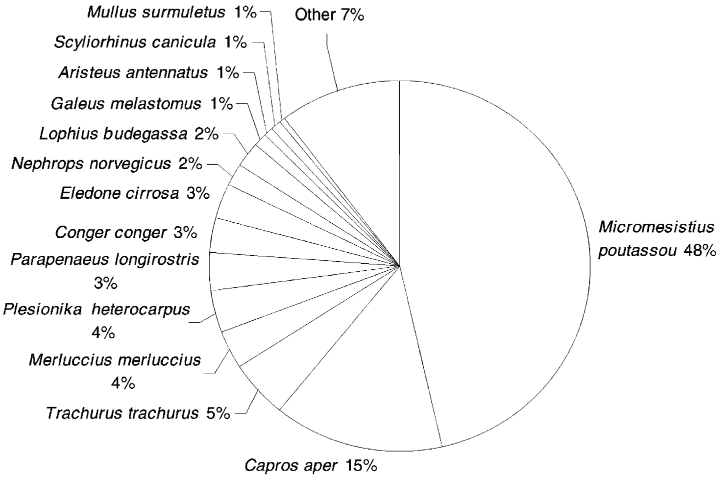


Fig. 4. Species composition by weight in cod end + cover, corresponding to a total catch of 21,660 kg in 133 hauls.

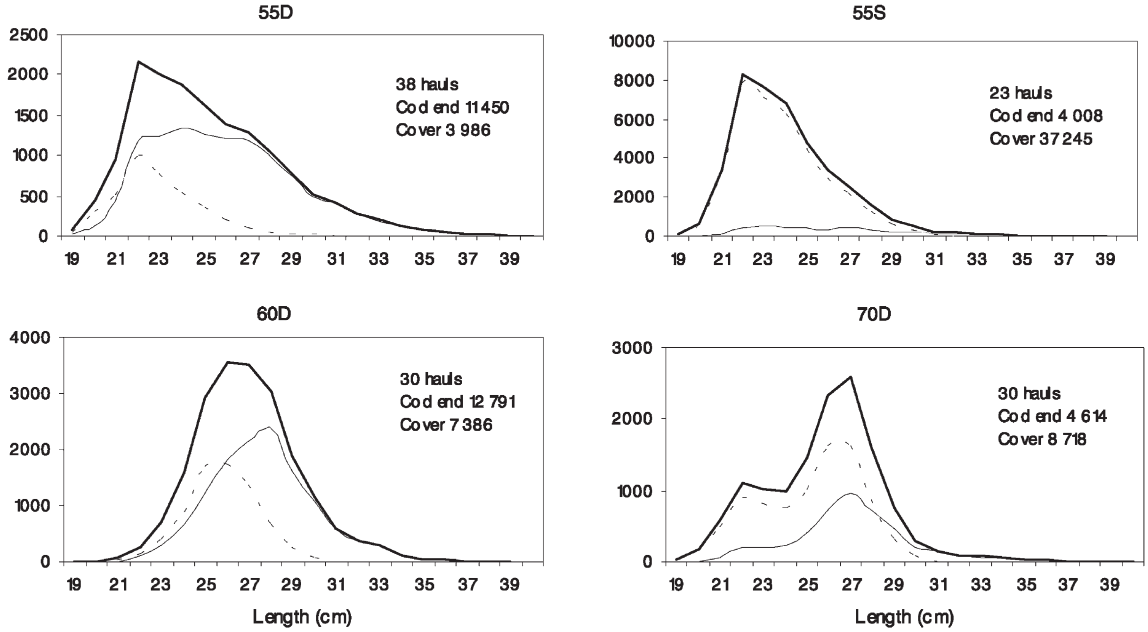


Fig. 5. Blue whiting (*M. poutassou*). Size structure of the populations that entered the different cod ends. Thin line indicates length frequency in cod end, dashed line in cover and thick line total numbers.

of the lower number of hauls carried out with this mesh size. The size selective properties of the 55S cod end are evident, with retention of a fraction of approximately only 10% of all the individuals that entered this cod end.

Length was depth-dependent, with smaller individuals from 20 to 25 cm caught at depths to 200 m, while the length range extends up to 30 cm at depths from 200 to 400 m. At depths >400 m, only larger fish with lengths from 25 to 35 cm were caught and in much smaller quantities.

A summary of hauls and catches is presented in Table 2. A total of 32 individual hauls where more than 100 blue whiting were caught was used in the analysis, accounting for 35% of the total number of hauls (N_t). This proportion varied by cod end according to the selective properties of each cod end, that in turn was found to be dependent on haul depth. As can be seen in Table 2, the percentage of individual hauls analysed was lower for the 55S (24%), from which most of the individuals escaped. The few individual hauls used for this mesh size were those carried out at greater depths, where the catches consisted mostly of larger individuals (>22 cm). By contrast, more than half (54%) of the total number of hauls with the 60D cod end could be used in the individual haul analysis.

Selectivity estimates are given in Table 3. The larger estimates for R_i indicate large within-haul variability and reflect the lower numbers of individuals in the cod end and/or in the cover in some of the hauls. However, in the cases of large numbers of individuals, the reason for these higher estimates may be due to over-dispersion, as given by the high values obtained for model deviance, exceeding those expected for binomially distributed data (Fryer, 1991). Over-dispersion here may indicate a failure of the assumption of independence in fish cod end entry, which can take place with schooling fish such as blue whiting.

L_{50} values estimated for the mean curves (Fryer and pooled data) were very close for the 60D cod end, while for the other cod ends some differences can be observed. For the estimates according to Fryer a continuous increase in L_{50} can be observed from 23.0 to 25.9, 27.3 and 30.2 cm when mesh size increased from 55 to 60 and 70 mm (diamond mesh) and mesh configuration changed to 55 mm square mesh, respectively. The SR also increased from 3.7 to 4.1 and

Table 2
Blue whiting. Summary of the hauls and catches for the different cod ends. N_t stands for the total number of hauls where the species was captured

Haul number	Date	Hour start	Depth (m)	Length range (cm)	Cod end catch			Cover catch		
					Blue whiting		Other (kg)	Blue whiting		Other (kg)
					kg	Number		kg	Number	
55D (55.2 mm)										
08A	March 21	15:25	303	20–29	28	306	22	34	410	10
09A	March 21	17:35	368	20–30	90	1037	23	30	335	7
16A	March 23	09:45	214	18–28	15	165	172	15	185	44
37A	March 28	08:00	221	17–25	14	201	117	19	284	78
39A	March 28	13:40	332	15–30	59	768	51	34	527	11
40A	March 29	15:40	335	19–30	59	669	45	20	277	10
14B	May 08	06:25	270	20–32	125	1179	44	72	733	17
n	7			15–32	390	4325	473	224	2751	178
$N > 100$ individuals	24	$N_t = 38$		15–40	1422	11450	2648	340	3986	1173
$p = n/N$	0.29				0.27	0.38		0.66	0.69	
55S (55.2 mm)										
58A	April 02	12:30	435	23–39	78	341	19	41	264	13
59A	April 02	14:35	500	25–39	19	79	38	6	38	10
60A	April 02	16:35	500	22–36	18	92	29	18	113	10
77B	May 23	11:40	318	22–31	13	80	16	10	71	10
78B	May 23	13:50	362	22–35	28	179	70	115	1180	38
n	5			22–39	156	771	172	190	1666	80
$N > 100$ individuals	21	$N_t = 23$		15–39	500	4008	1184	3694	37245	1033
$p = n/N$	0.24				0.31	0.19		0.05	0.04	
60D (60.3 mm)										
20B	May 09	06:45	199	23–32	160	1192	44	62	543	11
32B	May 13	06:40	242	19–28	11	119	101	12	158	101
33B	May 13	08:55	349	22–34	84	620	47	27	235	14
34B	May 13	10:55	341	22–31	110	778	41	143	1218	22
37B	May 14	07:15	258	21–29	7	65	142	3	46	80
38B	May 14	09:10	251	20–29	34	370	177	40	456	72
39B	May 14	11:00	296	21–30	96	872	30	88	792	16
40B	May 14	13:05	382	23–30	166	1140	17	32	258	7
43B	May 15	08:35	333	23–35	60	378	75	6	44	7
44B	May 15	10:25	301	23–33	42	167	155	55	374	63
45B	May 15	11:45	299	24–33	253	1710	61	286	2116	64
46B	May 15	14:55	315	23–35	33	202	50	29	215	9
47B	May 15	17:10	317	23–34	87	652	24	47	396	12
54B	May 18	09:50	476	24–35	99	524	35	21	142	6
n	14			19–35	1242	8789	997	851	6993	486
$N > 100$ individuals	26	$N_t = 30$		19–36	1992	12971	1643	898	7386	683
$p = n/N$	0.54				0.62	0.68		0.95	0.95	
70D (70.6 mm)										
07B	May 05	08:40	296	21–31	47	372	40	84	818	18
36A	March 27	16:40	310	19–28	20	253	25	26	341	15
57B	May 19	06:40	290	23–35	28	213	20	31	262	19
59B	May 19	10:25	308	21–31	62	454	35	48	372	21
61B	May 19	14:05	315	23–31	26	192	18	22	165	6
63B	May 20	08:30	296	23–33	80	565	47	245	1928	28
n	6			19–35	263	2049	184	456	3886	108
$N > 100$ individuals	20	$N_t = 30$		18–40	638	4614	1674	1014.7	8718	1346
$p = n/N$	0.30				0.41	0.44		0.45	0.45	

Table 3
Selectivity estimates for blue whiting. The 95% CI for L_{50} and SR are in brackets

Haul number	L_{50}	SR	SF	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}	Deviance	d.f.	p-Value	Sampling proportion	
												Cod	Cover
55D													
08A	24.7 (24.0–25.4)	5.1 (2.9–7.2)	4.5	−10.718	0.434	3.772	−0.1563	0.00650	9.1	8	0.33	0.5	0.5
09A	23.6 (23.3–24.0)	3.0 (2.5–3.5)	4.3	−17.188	0.727	1.821	−0.0716	0.00283	4.4	9	0.89	0.2	1.0
16A	23.7 (23.3–24.1)	3.7 (2.6–4.8)	4.3	−14.063	0.594	3.517	−0.1496	0.00638	7.2	9	0.62	1.0	1.0
37A	22.4 (21.7–23.1)	5.0 (2.6–7.4)	4.1	−9.914	0.443	3.908	−0.1800	0.00832	9.2	7	0.24	1.0	1.0
39A	21.8 (21.5–22.1)	3.3 (2.4–4.1)	3.9	−14.709	0.675	3.511	−0.1575	0.00709	30.7	12	0.00	1.0	1.0
40A	22.4 (22.2–22.7)	2.1 (1.7–2.6)	4.1	−23.328	1.040	4.863	−0.2111	0.00918	14.7	10	0.14	1.0	1.0
14B	23.7 (22.9–24.5)	7.8 (5.0–10.6)	4.3	−6.713	0.283	1.392	−0.0546	0.00215	13.9	11	0.24	0.4	1.0
MC Fryer	23.0 (22.3–23.9)	3.7 (2.6–4.9)	4.2	−13.530	0.588	4.234	−0.1915	0.00874					
MC pooled	21.7 (21.5–21.9)	5.3 (5.0–5.7)	3.9	−8.916	0.411	0.115	−0.0048	0.00021					
D						26.480	−1.2049	0.05534					
55S													
58A	30.3 (30.0–30.5)	3.5 (3.0–4.0)	5.5	−19.142	0.632	1.526	−0.0497	0.00162	6.4	13	0.93	1.0	1.0
59A	30.5 (29.9–31.1)	3.3 (2.3–4.3)	5.5	−20.344	0.667	8.960	−0.2858	0.00914	6.3	13	0.94	1.0	1.0
60A	30.6 (29.9–31.4)	4.6 (2.9–6.3)	5.6	−14.667	0.479	5.864	−0.1929	0.00637	11.8	12	0.46	1.0	1.0
77B	26.1 (22.9–29.3)	14.3 (2.0–30.7)	4.7	−4.005	0.154	3.747	−0.1380	0.00513	8.1	6	0.23	1.0	1.0
78B	30.8 (30.3–31.3)	4.1 (3.4–4.8)	5.6	−16.566	0.538	1.343	−0.0478	0.00170	5.2	12	0.95	1.0	0.5
MC Fryer	30.2 (29.3–30.7)	4.5 (2.7–6.2)	5.5	−14.922	0.493	9.718	−0.3090	0.00983					
MC pooled	31.7 (30.6–32.9)	6.9 (5.7–8.0)	5.8	−10.167	0.320	0.412	−0.0160	0.00063					
D						44.849	−14.219	0.04511					
60D													
20B	24.2 (23.6–24.9)	4.9 (3.4–6.4)	4.0	−10.824	0.447	2.371	−0.0913	0.00352	4.9	8	0.77	0.3	0.4
32B	23.4 (22.9–23.9)	3.7 (2.2–5.3)	3.9	−13.803	0.591	6.099	−0.2663	0.01166	6.6	8	0.58	1.0	1.0
33B	26.0 (25.5–26.5)	2.6 (1.8–3.4)	4.3	−21.902	0.843	9.886	−0.3654	0.01353	22.7	11	0.02	0.5	1.0
34B	27.5 (27.1–27.9)	3.6 (2.5–4.6)	4.6	−16.997	0.618	4.233	−0.1569	0.00583	13.0	8	0.11	0.4	0.5
37B	23.3 (22.3–24.3)	4.0 (1.2–6.9)	3.9	−12.741	0.547	15.277	−0.6418	0.02704	7.5	7	0.38	1.0	1.0
38B	24.8 (23.9–25.7)	7.3 (2.4–12.2)	4.1	−7.455	0.301	4.364	−0.1811	0.00753	10.3	8	0.24	1.0	0.5
39B	25.7 (25.2–26.2)	5.0 (2.9–7.0)	4.3	−11.405	0.443	4.018	−0.1564	0.00610	15.4	8	0.05	0.5	0.5
40B	25.1 (24.4–25.9)	3.8 (2.8–4.9)	4.2	−14.364	0.572	3.655	−0.1325	0.00482	13.1	10	0.22	0.5	1.0
43B	23.8 (21.8–25.8)	4.3 (2.1–6.4)	4.0	−12.275	0.515	10.418	−0.3785	0.01381	6.2	9	0.72	1.0	0.5
44B	28.6 (27.9–29.4)	4.9 (3.3–6.5)	4.7	−12.848	0.449	3.100	−0.1152	0.00429	6.2	9	0.72	1.0	0.5
45B	28.1 (27.6–28.6)	4.2 (2.6–5.8)	4.7	−14.789	0.526	5.695	−0.2052	0.00741	14.3	8	0.07	0.2	0.2
46B	28.2 (27.8–28.7)	3.4 (2.3–4.5)	4.7	−18.315	0.649	6.851	−0.2433	0.00866	15.2	11	0.17	1.0	1.0
47B	26.0 (25.7–26.3)	3.5 (2.8–4.2)	4.3	−16.501	0.634	2.291	−0.0853	0.00319	3.5	9	0.94	0.3	0.5
54B	26.8 (26.2–27.3)	4.0 (3.2–4.8)	4.4	−14.680	0.548	2.160	−0.0743	0.00256	5.3	10	0.87	0.5	1.0
MC Fryer	25.9 (24.9–26.8)	4.1 (3.7–4.6)	4.3	−13.691	0.530	0.743	−0.0246	0.00089					
MC pooled	25.3 (24.8–25.7)	5.1 (4.1–6.2)	4.2	−10.788	0.427	1.183	−0.0446	0.00169					
D						5.888	−0.1728	0.00588					

70D													
07B	27.4 (26.4–28.4)	5.0 (2.8–7.2)	3.9	−12.093	0.441	5.024	−0.1941	0.00753	19.3	9	0.02	0.5	0.5
36A	24.1 (23.4–24.8)	7.3 (4.0–10.5)	3.4	−7.297	0.303	1.863	−0.0803	0.00348	6.6	8	0.58	1.0	1.0
57B	27.2 (26.8–27.7)	4.7 (3.4–5.9)	3.9	−12.863	0.473	2.416	−0.0901	0.00337	8.5	11	0.66	1.0	1.0
59B	27.0 (26.4–27.6)	5.7 (3.1–8.3)	3.8	−10.459	0.388	4.313	−0.1567	0.00571	11.9	7	0.10	1.0	1.0
61B	27.0 (26.6–27.6)	3.7 (2.0–5.3)	3.8	−16.279	0.601	9.735	−0.3563	0.01307	8.8	7	0.27	1.0	1.0
63B	29.8 (29.4–30.3)	4.0 (3.4–4.7)	4.2	−16.305	0.547	1.188	−0.0430	0.00156	5.9	9	0.75	1.0	0.4
MC Fryer	27.3 (25.6–28.7)	5.0 (4.2–5.9)	3.9	−11.898	0.435	1.654	−0.0476	0.00142					
MC pooled	28.2 (27.6–28.7)	7.3 (5.9–8.6)	4.0	−8.530	0.303	0.505	−0.0191	0.00073					
D						7.387	−0.1908	0.00493					

5.0, while for the square mesh cod end the estimated SR was 4.5 cm. SR estimates for the mean curves according to Fryer are consistently lower than those estimated for pooled data, denoting steeper curves and therefore sharper selectivity. In the 55D and 55S cod ends the variance estimates given by R_i are much higher for the mean curves according to Fryer when compared to those estimated for pooled data, while in the 60 and 70D cod ends the differences between the two estimates are small.

Individual haul and mean curves (Fryer and pooled data) are presented in Fig. 6. The observed variability in positions and shapes of the individual curves within the same cod end, which is expressed by the D matrices (Table 3), mainly for the 55D and 55S cod ends, suggests strong influence of variables other than mesh size and mesh configuration on the estimated selectivity parameters.

For the analysis of between-haul variation of L_{50} and SR using Fryer's (1991) model, the model which described the data best was

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_1 m_i + \alpha_3 t_i + \alpha_4 d_i + \alpha_5 c_i \\ \alpha_2 m_i \end{pmatrix}$$

The alpha parameter estimates are given in Table 4. L_{50} was positively affected by mesh size and mesh configuration as well as by trawling depth and cod end catch, while mesh size was the only variable which significantly affected SR. Of all these variables, mesh size was the one that most affected selectivity, while mesh configuration, cod end catch and depth were much less important, as can be observed by the t-values in Table 4.

3.3. Horse mackerel

Horse mackerel was caught at depths from 152 to 706 m. While the vast majority of the individuals caught had lengths from 14 to 21 cm for all mesh sizes (Fig. 7), with a mode between 16 and 18 cm, a small proportion of larger individuals from approximately 22–30 cm were also caught, mainly in the 70D and 55S cod ends. The higher selective properties of these two cod ends are evident when compared to the other two, with a fraction of only 0.22 and 0.25, respectively, of the total numbers of individuals retained.

The number of individual hauls where it was possible to estimate selectivity was very low, with 5, 3 and 2 hauls for the 55D, 60D and 55S cod ends, respectively. Mean selectivity curves were therefore estimated using pooled data.

L_{50} increased from 18.0 to 19.8 and 21.9 cm (Table 5) with the corresponding increase in mesh size from 55 to 60 and 70D (diamond mesh). L_{50} for the 55S cod end was 21.7 cm, a value very close to that estimated for the 70D cod end, and the same was also true for the 95% confidence intervals (Table 5). SR estimates are very similar for the 55 and 60D cod ends (3.8 and 3.6 cm, respectively) and for the 70D and 55S ones (4.9 and 5.0 cm). The fitted selectivity curves together with the observed retention values for all mesh sizes are shown in Fig. 8.

Table 4
Parameter estimates for blue whiting

Parameter	Estimate	Standard error	t-Value
α_1 (mesh size)	0.31751	2.31×10^{-2}	13.730
α_2 (mesh size)	0.06451	2.56×10^{-3}	25.155
α_3 (mesh config.)	6.01618	1.03	5.827
α_4 (depth)	0.01231	4.28×10^{-3}	2.879
α_5 (cod end catch)	0.01684	4.40×10^{-3}	3.829

3.4. European hake

Hake was caught in much lower numbers than the previous species, at depths from 152 to 662 m, but mostly at depths down to 200 m, where many juveniles (lengths from 5 to 25 cm) were caught in the 55D, 70D and 55S cod ends, while the length of the individuals caught in the 60D cod end ranged from 10 to 25 cm (Fig. 9). A small fraction of larger individuals from 30 to 70 cm was also retained in all cod ends.

In spite of the observed differences between cod ends both in the total number of individuals captured and in the relative proportions of juveniles and adults, a common selection pattern can be observed in all cod ends with total escapement of individuals up to 12–13 cm in length, partial retention (cod end dependent) of those from 13 to 25 cm and total retention of all individuals above 25 cm (Fig. 9).

Most of the hake catches were obtained in the 70D and 55S cod ends, but since only very small percentages were retained, selectivity could only be estimated for the 55 and 60D cod ends using pooled

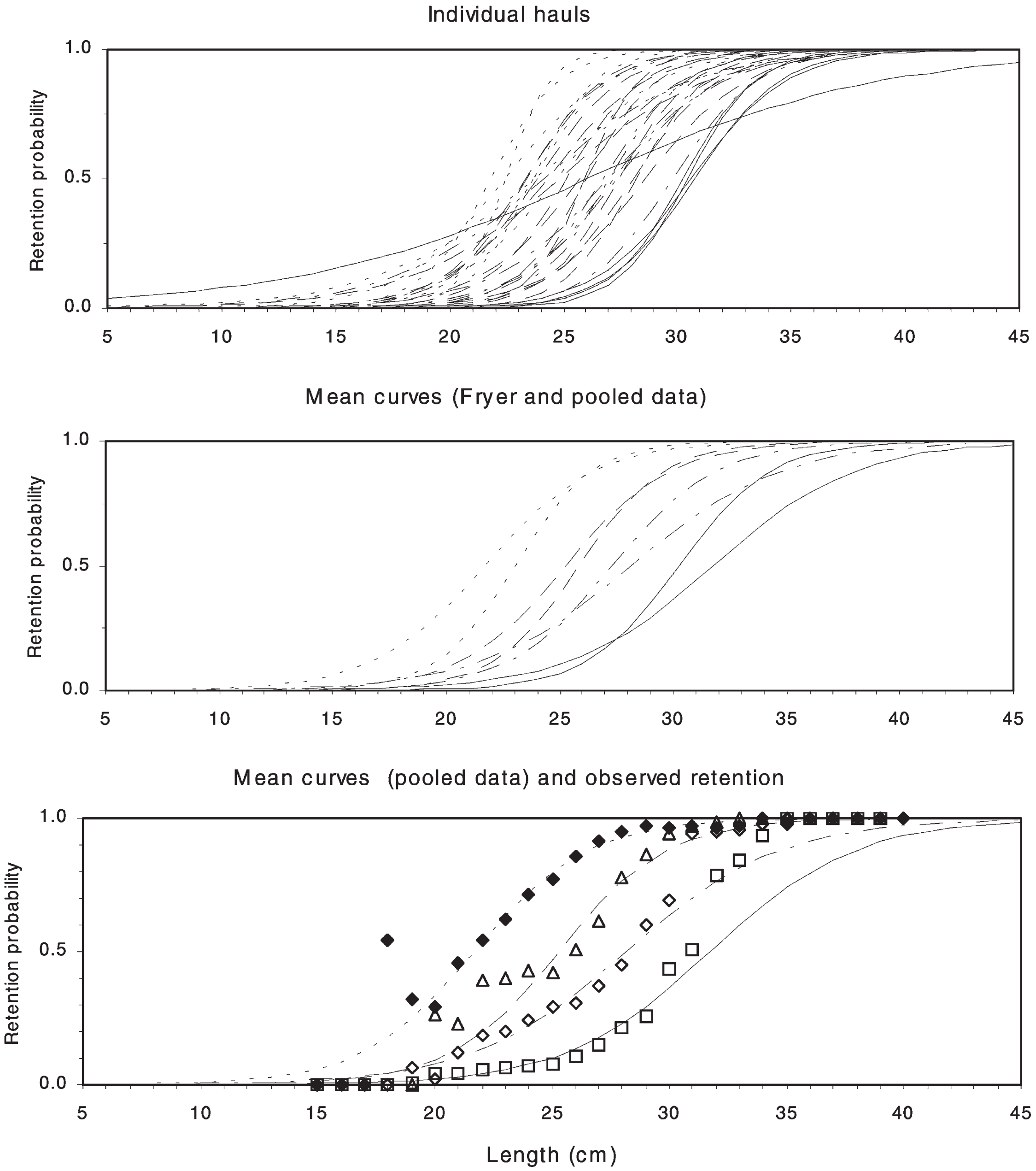


Fig. 6. Blue whiting (*M. poutassou*). Selectivity curves in the four cod ends for individual hauls and mean curves. Black lines indicate mean curves according to Fryer and grey lines mean curves based on pooled data: (- - -) 55D; (— — —) 60D; (—·—) 70D; (—) 55S. Observed retention is expressed as black lozenges (55D), triangles (60D), white lozenges (70D) and squares (55S).

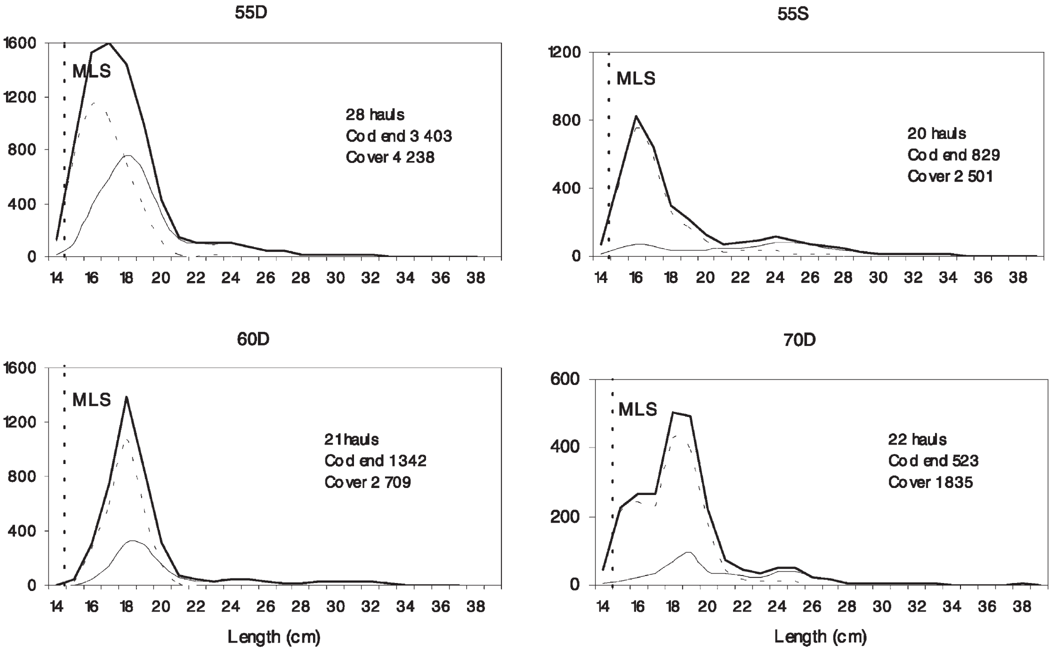


Fig. 7. Horse mackerel (*T. trachurus*). Size structure of the populations that entered the different cod ends. Thin line indicates length frequency in cod end, dashed line in cover and thick line total numbers.

Table 5
Selectivity parameter estimates for the horse mackerel *T. trachurus*

Selectivity estimates	Cod end			
	55D	60D	70D	55S
Retained				
$<$MLS	14	0	4	6
$\geq$MLS	3389	1342	519	823
Escapees				
$<$MLS	114	3	45	70
$\geq$MLS	4124	2706	1790	2431
v_1	-10.497	-12.0258	-9.788	-9.444
v_2	0.583	0.608	0.446	0.435
R_{11}	0.115	0.465	0.386	0.230
R_{12}	-0.0065	-0.025	-0.0197	-0.0116
R_{22}	0.00037	0.00135	0.00102	0.00060
L_{50}	18.0	19.8	21.9	21.7
CI L_{50}	17.9–18.1	19.6–20.0	21.4–22.4	21.2–22.2
SR	3.8	3.6	4.9	5.0
CI SR	3.5–4.0	3.2–4.1	4.2–5.7	4.5–5.6
SF	3.3	3.3	3.1	3.9
Deviance	27.9	35.0	38.3	60.5
d.f.	22	22	22	25
p-Value	0.18	0.04	0.02	0.00

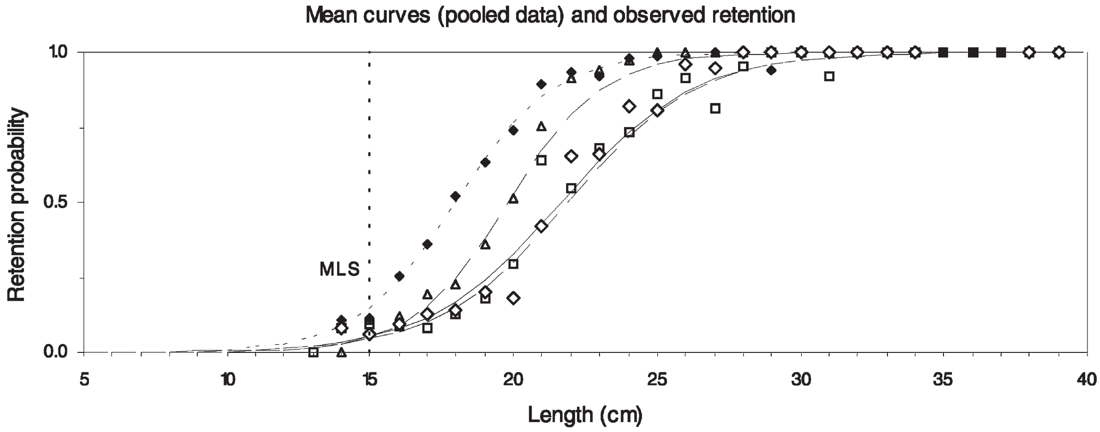


Fig. 8. Horse mackerel (*T. trachurus*). Selectivity curves based on pooled data, together with observed retention in the four cod ends: (- - -) 55D; (— — —) 60D; (—·—·—) 70D; (—) 55S. Observed retention is expressed as black lozenges (55D), triangles (60D), white lozenges (70D) and squares (55S).

data (Fig. 10). L_{50} increased from 15.9 to 17.4 cm when the 55D cod end was replaced by the 60D cod end, while a small increase in SR from 3.0 to 3.8 cm was observed, with a constant selection factor of 2.9 (Table 6).

3.5. *Red shrimp*

Red shrimp was caught at depths from 317 to 706 m in a wide length class range from 18 to 66 mm in all cod ends, with modes between 42 and 48 mm (Fig. 11).

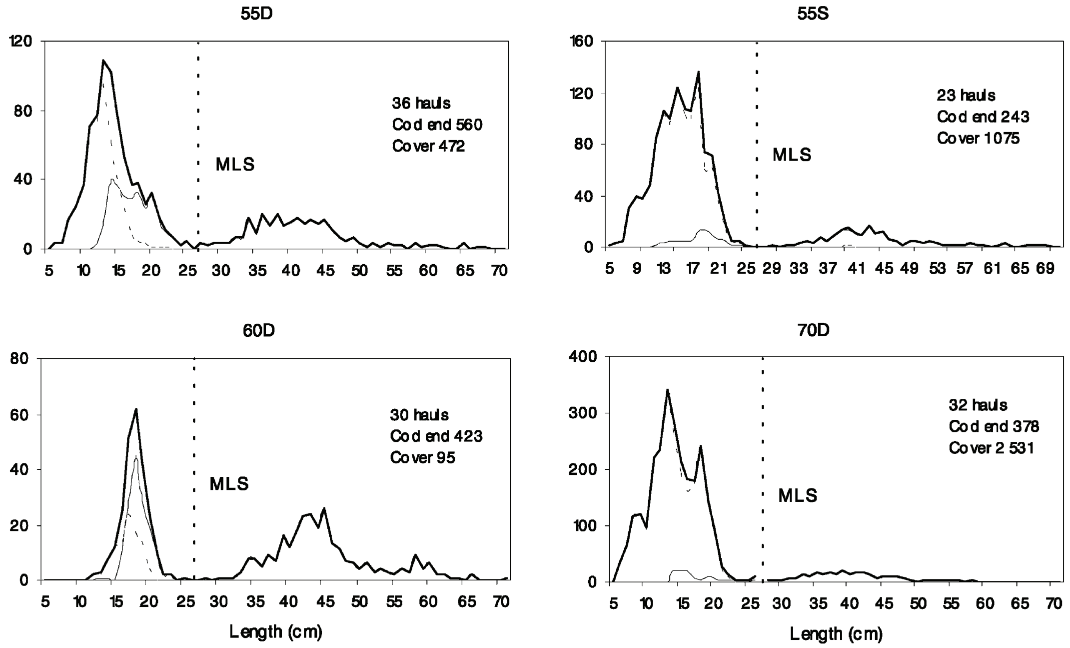


Fig. 9. European hake (*M. merluccius*). Size structure of the populations that entered the different cod ends. Thin line indicates length frequency in cod end, dashed line in cover and thick line total numbers.

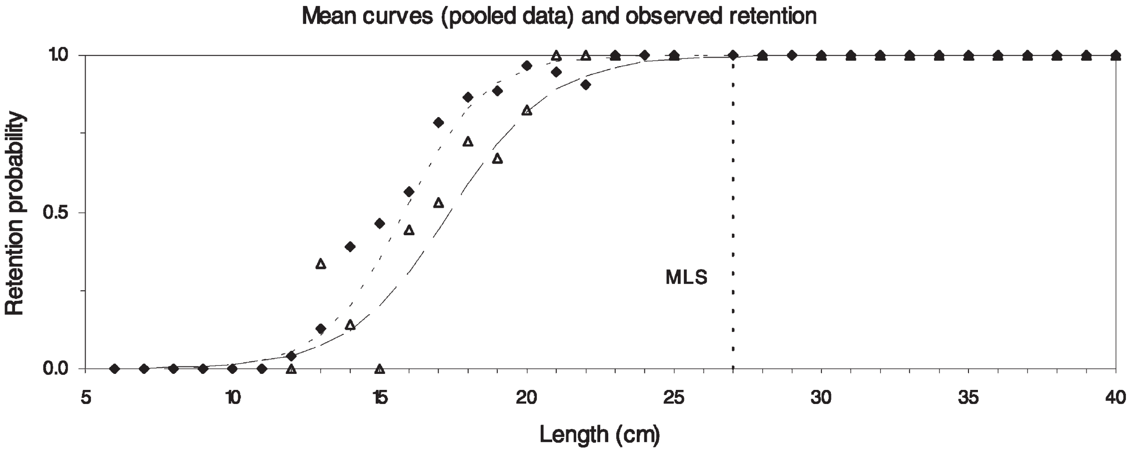


Fig. 10. European hake (*M. merluccius*). Selectivity curves based on pooled data, together with observed retention: (- - -) 55D; (— — —) 60D. Observed retention is expressed as black lozenges (55D) and triangles (60D).

Retention was very high in all cod ends, particularly in the 55 and 60D where a fraction of more than 0.9 of the total number of individuals entered was retained. Selectivity estimates based on pooled data are presented for all cod ends in Table 7, and the selectivity curves in Fig. 12. For the 55D cod end the L_{50} (13.8 mm) and SR (22.6 mm) estimates had wide confidence intervals (8.5–19.1 and 17.4–27.8 mm, respectively). L_{50} estimates of 24.6, 29.8 and 32.3 mm were obtained for the 60D, 70D and 55S cod ends, respectively, with narrow and non-overlapping confidence intervals (Table 7), showing an increase in selectivity with increasing mesh size or change in mesh configuration. Estimates of SR were 11.5, 9.8 and 9.1, with overlapping confidence intervals (Table 7).

Table 6
Selectivity parameter estimates for the European hake *M. merluccius*

Selectivity estimates	Cod end			
	55D	60D	70D	55S
Retained				
<MLS	281	147	108	69
≥MLS	279	277	270	174
Escapees				
<MLS	472	95	2531	1074
≥MLS	0	0	0	1
v_1	−11.660	−10.068	–	–
v_2	0.735	0.579	–	–
R_{11}	0.296	0.967	–	–
R_{12}	−0.0192	−0.0532	–	–
R_{22}	0.00126	0.00294	–	–
L_{50}	15.9	17.4	–	–
CI L_{50}	15.7–16.1	17.1–17.7	–	–
SR	3.0	3.8	–	–
CI SR	3.0	3.8	–	–
SF	2.9	2.9	–	–
Deviance	23.6	14.6	–	–
d.f.	56	49	–	–
p-Value	1	1	–	–

4. Discussion

Different responses to an increase in cod end mesh size or alteration in mesh configuration were found for the four species. For blue whiting and red shrimp L_{50} increased with mesh size for the diamond cod ends and with the use of 55 mm square mesh cod end, while for horse mackerel the 70D and 55S cod ends were very similar in terms of selectivity. For hake a small but noticeable increase in L_{50} was found with an increase in mesh size from 55 to 60 mm.

Except for the blue whiting, the data structure did not allow for an individual haul analysis, since the number of individual hauls for which it was possible to estimate selectivity parameters was very low. Selectivity estimates were then based on pooled data, resulting in the loss of all information on between-haul variation. Petrakis and Stergiou (1997) experienced

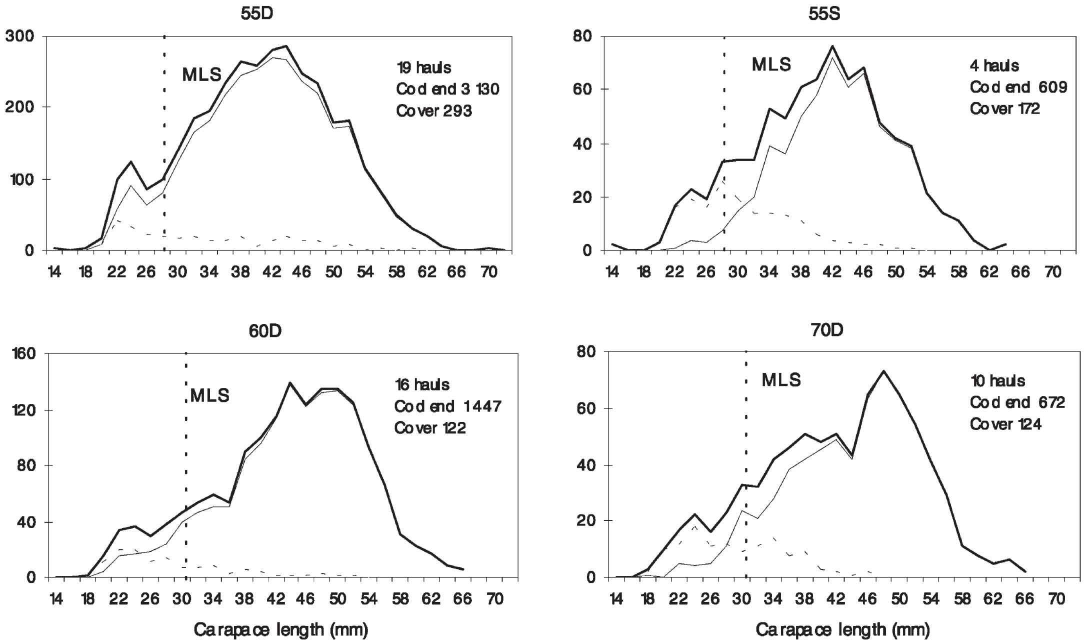


Fig. 11. Red shrimp (*A. antennatus*). Size structure of the populations that entered the different cod ends. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers.

Table 7
Selectivity parameter estimates for the red shrimp *A. antennatus*

Selectivity estimates	Cod end			
	55D	60D	70D	55S
Retained				
<MLS	257	66	21	13
≥MLS	2873	1381	651	596
Escapees				
<MLS	120	69	61	71
≥MLS	173	53	63	101
v_1	−1.341	−4.681	−6.698	−7.808
v_2	0.097	0.190	0.224	0.241
R_{11}	0.154	0.108	0.344	0.190
R_{12}	−0.0041	−0.0031	−0.0097	−0.0052
R_{22}	0.00011	0.000009	0.00028	0.00014
L_{50}	13.8	24.6	29.8	32.3
CI L_{50}	8.5–19.1	23.4–25.8	28.6–31.1	31.6–33.0
SR	22.6	11.5	9.8	9.1
CI SR	17.4–27.8	10.3–12.8	8.3–11.3	8.2–10.1
SF	0.25	0.41	0.42	0.59
Deviance	57.4	11.2	18.5	8.8
d.f.	26	23	23	21
p-Value	0.00	0.98	0.73	0.99

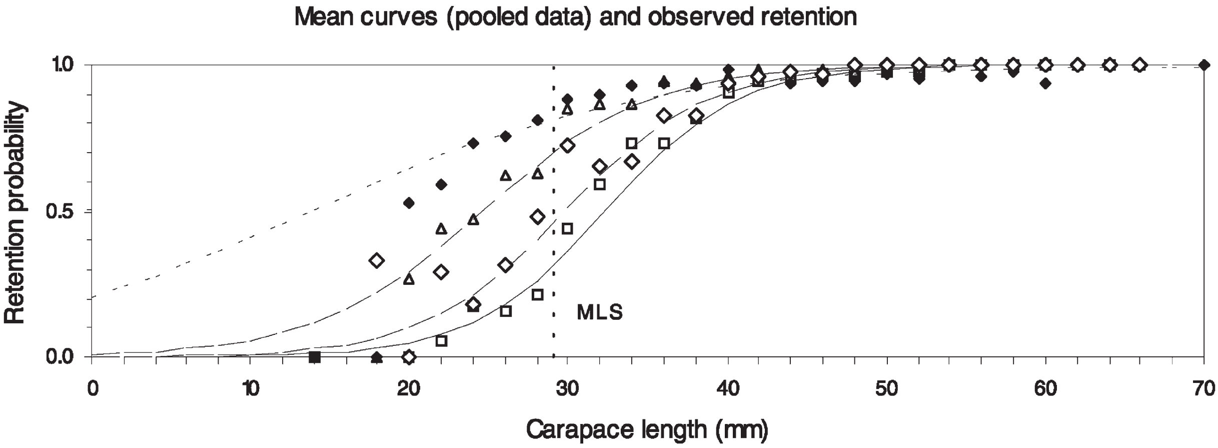


Fig. 12. Red shrimp (*A. antennatus*). Selectivity curves based on pooled data, together with observed retention in the four cod ends: (- - -) 55D; (— — —) 60D; (—·—·—) 70D; (—) 55S. Observed retention is expressed as black lozenges (55D), triangles (60D), white lozenges (70D) and squares (55S).

this situation when analysing selectivity data for hake, blue whiting, Mediterranean pout *Trisopterus minutus capelanus* and megrim *Lepidorhombus boscii* in Mediterranean waters.

For blue whiting, L_{50} was found to be positively affected by two external variables, trawling depth and cod end catch. The relationships between L_{50} and these two variables are shown in Fig. 13. A general trend for an increase in L_{50} with cod end catch is shown for all cod ends, while an increase in L_{50} with depth can be observed only for the 60D and the 55S cod ends, fished at depths from 199 to 476 and 318 to 500 m, respectively. For the 55D cod end (214–368 m) no similar trend was found and all individual hauls with the 70D cod end for which L_{50} could be estimated were carried out at practically the same depth of approximately 300 m.

In both cases, a cod end effect on L_{50} can be observed independent of cod end catch or depth, which reflects the fact that selectivity is affected both by mesh size and mesh configuration. Furthermore, the range of common depth and catch values for all cod ends was low. With regards to depth, this is a result of the observed differences in data structure between cod ends. For example, the individual hauls for which it was possible to estimate L_{50} in the 55S cod end were those carried out at greater depths, where the catches consisted mostly of larger individuals, since at lower depths most of the individuals were small and escaped. Inversely, for the 55 and 60D cod ends, L_{50} could only be estimated for the hauls carried out at lower depths (except one haul at 476 m for the 60D cod end), since at greater depths the size of individuals captured resulted in almost total retention within these mesh sizes.

The higher cod end catches associated with the 55 and 60D mesh sizes reflects the fact that catch in the cod end itself depends on cod end selectivity. While in these cod ends most of the individuals that entered the cod end were retained, in the 70D and the 55S cod ends most of the catch escaped through the meshes.

The results obtained for blue whiting are in accordance with those reported by O'Neill and Kynoch (1996), who found a significant increase in L_{50} with cod end catch for haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*), species that are similar to blue whiting in terms of both body shape and swimming behaviour, in small catches from approximately 100–400 kg for both species. These authors suggest that this tendency may not continue with increasing catch size, and they explain the effects of this variable on L_{50} in terms of the correspondent alteration to the cod end geometry and degree of mesh opening. As the catch builds up the meshes in front of the cod end open wider and selectivity increases, up to a point where the maximum mesh opening is

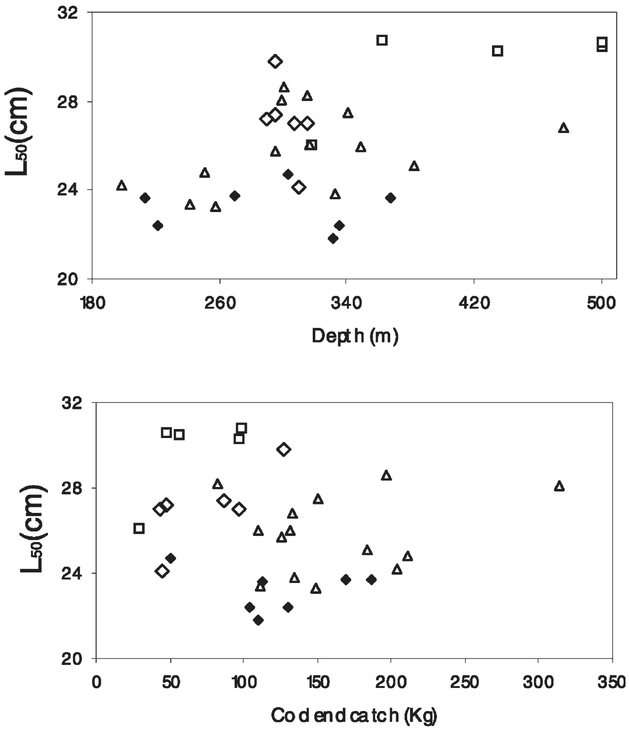


Fig. 13. Blue whiting (*M. poutassou*). L_{50} values plotted against fishing depth and cod end catch size for all cod ends tested. Black lozenges, triangles and white lozenges correspond to 55, 60 and 70 mm diamond cod ends, respectively, and squares to the 55 mm square mesh cod end.

achieved and selectivity levels out or decreases with any further increase in catch size.

However, evidence for the opposite effect of catch on L_{50} has been found in other studies. Suuronen et al. (1991) reported a significant reduction in L_{50} for herring (*Clupea harengus*) with cod end catches up to 1600 kg and similar trends were found for whiting by Madsen and Moth-Poulsen (1994) and for the Baltic sea cod (*Gadus morhua*) by Madsen et al. (1998) with cod ends fitted with a square mesh window, at catch ranges from 200 to 600 and 300 to 800 kg, respectively.

Cod end catches recorded in this study are very low, ranging from 29 to 314 kg for individual hauls analysed for blue whiting. The lower limit is certainly well below the normal catch weight in the commercial fishery, where tow duration can exceed 4 h. The effects of this variable on cod end selectivity may become more evident when analysing commercial catches and there is therefore a need for the analysis of commercial data before any definitive conclusions concerning the effects of this variable on selectivity parameters can be drawn.

No other studies have reported on the effects of fishing depth on L_{50} for fish species. However, Campos et al. (2002) found that depth significantly increased the selection range for the rose shrimp *P. longirostris*, a species for which the length distribution was found to be depth-dependent, as was the case for the blue whiting in the present study.

No significant effects of the variable cruise on L_{50} or SR were detected. Although the data are from two cruises, there were no changes in the vessel, gear and rigging as well as in the fishing tactics. The time interval between cruises (approximately one month) was not expected to be enough for changes in specific condition to occur and that could be responsible for changes in selectivity.

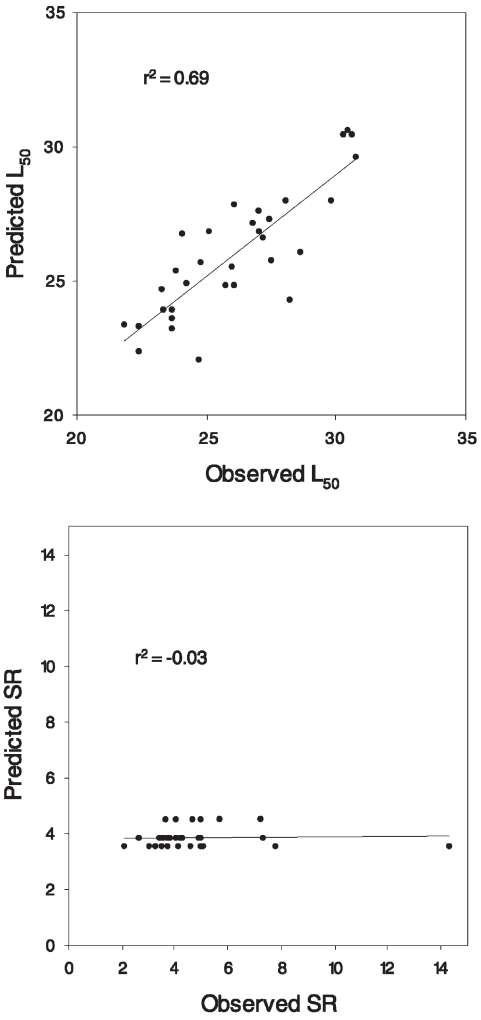


Fig. 14. Blue whiting (*M. poutassou*). Predicted values for the selectivity parameters L_{50} and SR plotted against observed values.

The predicted values for L_{50} and SR obtained for the model are plotted against the observed values in Fig. 14. Although the observed relationship for L_{50} is significant ($r^2 = 0.69$), the same was not true for SR ($r^2 = -0.03$). This is probably related to the higher variability of L_{50} when compared to SR, which has resulted in the estimation of significant effects of the different variables, including depth and cod end catch, in L_{50} rather than in SR.

Of the four species, only blue whiting is not subject to an MLS since it has no commercial value and is therefore discarded. MLSs for hake and horse mackerel are 27 and 15 cm respectively, while for the red shrimp MLS is fixed at 29 mm of CL. For horse mackerel, almost all undersized individuals that entered the 55D cod end escaped, while for hake, a significant proportion of the individuals between 13 and 20 cm and all the individuals above 20 cm were retained in this cod end as well as in the 60D. It is important to note that, due to the data structure (Fig. 9), selectivity estimates for this species were almost entirely based on individuals from 5 to 25 cm that accounted for the bulk of the catches. The complete absence of individuals between 25 and 30 cm prevented the estimation of selectivity for the 70D and 55S cod ends.

With regards to the red shrimp, a fraction close to 0.7 of all the individuals below 29 mm of carapace was retained in the 55D cod end, while in the 60D cod end the estimated L_{50} of 24.6 cm is below the MLS for this species, suggesting poor selectivity in both mesh sizes. The use of the 70D and 55S cod ends improves this situation by increasing the L_{50} estimate to values near the established MLS fixed for this species.

For blue whiting, the use of the 55 and 60D cod ends resulted in escapements of 25 and 36%, respectively, while escapement increased to 65% for the 70D cod end and 90% for the 55S cod end.

The data structure did not allow selectivity analysis for a number of other commercial by-catch species such as the giant red shrimp, *Aristeomorpha foliacea*, the monkfish *L. budegassa*, the striped red mullet *Mullus surmuletus* and the seabreams *Pagellus acarne* and *Pagellus bogaraveo*, where retention was high in all mesh sizes. In the case of the bogue (*Boops boops*) almost all individuals were retained in the 55 and 60D cod ends. All these species were caught within length ranges almost entirely above their respective MLSs, and in much lower numbers than those of the four species analysed.

5. Conclusions

For horse mackerel, the most abundant commercially valuable by-catch species, the use of the 55 mm diamond mesh does not seem to pose any problem since the estimated retention probability for a length of 15 cm, corresponding to the MLS, was approximately 0.25. On the other hand, the results for hake and red shrimp for the 55 and 60D cod ends showed that these two mesh sizes are not compatible with the corresponding MLS of 27 cm and 29 mm for these species.

Previous results on selectivity for the two main target species in this fishery, the rose shrimp and the Norway lobster (Campos et al., 2002), obtained during the same set of experiments, suggested the need for an increase in mesh size from 55 to 70 mm in order to respect the MLS of 24 mm CL for rose shrimp that would result in minor losses in Norway lobster retention above the MLS of 20 mm. According to the data presented, the 70D mesh size would also contribute to reducing the amount of retained hake below 27 cm and in addition increase the escapement of blue whiting. Therefore, the only commercial species captured in large amounts for which an increase in cod end mesh size to 70 mm would significantly reduce the catch of legal sized individuals is the horse mackerel, which is the least valuable of the commercial by-catch species. However, when applying minimum cod end mesh size regulations, it is important to bear in mind that mesh size is only one of the several factors determining cod end selectivity. Besides, these regulations should be based on existing information on post-escapement survival of fish (Chopin and Arimoto, 1995; Suuronen, 1995), for which there is currently no data for Portuguese waters.

Trawling depth and cod end catch were identified as being responsible for changes in L_{50} for blue whiting, the only species for which the selectivity estimated was based on an individual haul analysis. However, it is important to note that the main focus of the study was on mesh size and mesh configuration and not on the effects of depth and cod end catch. The effects of such factors require further study before definitive conclusions can be drawn.

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Selectivity of diamond and square mesh cod ends for horse mackerel (*Trachurus trachurus*), European hake (*Merluccius merluccius*) and axillary seabream (*Pagellus acarne*) in the shallow groundfish assemblage off the south-west coast of Portugal*

AIDA CAMPOS and PAULO FONSECA

IPIMAR, Avenida de Brasília, 1449-006, Lisbon, Portugal. E-mail: acampos@ipimar.pt

SUMMARY: The effects of an increase in cod end mesh size from 65 to 70 and 80 mm and a change of mesh configuration from 65 mm diamond to 65 mm square mesh on the size selectivity of horse mackerel (*Trachurus trachurus*), hake (*Merluccius merluccius*) and axillary seabream (*Pagellus acarne*) of the shallow groundfish assemblage off the Portuguese southwest coast were evaluated. The increase in mesh size had a small but significant effect on size selectivity for the three species, while the change in mesh configuration led to a much more pronounced increase in the selectivity parameters. For horse mackerel, the L_{50} estimates ranged from 14.4 to 16.0 cm in the diamond mesh cod ends—values that are close to the minimum landing size of 15 cm. For hake, L_{50} of 17.0 and 18.3 cm were estimated for the 70 and 80 mm diamond cod ends respectively, while for the axillary seabream the L_{50} estimated was 13.9 cm for the 80 mm diamond mesh cod end. These values are well below the minimum landing sizes of 27 and 18 cm for these species. The corresponding estimates in the square mesh cod end were 21.9, 32.4 and 19.6 cm, with the loss of a high percentage (76%) of horse mackerel above the minimum landing size. For all the cod ends tested, the observed retention was presented as a function of maximum girth/mesh perimeter, which allowed a better understanding of the selection process for the species in study. Selectivity estimates for horse mackerel and hake were also compared to those obtained by Campos *et al.* (2003) for the same species in 1993 off the south coast, where they are captured as a by-catch in the crustacean fishery.

Key words: cod end selectivity, mesh size, mesh configuration, length-girth relationships, by-catch, *Trachurus trachurus, Merluccius merluccius*, *Pagellus acarne.*

RESUMEN: SELECTIVIDAD DE COPOS CON MALLA DE DIAMANTE Y CUADRADA PARA JUREL (*TRACHURUS TRACHURUS*), MERLUZA EUROPEA (*MERLUCCIUS MERLUCCIUS*) Y ALIGOTE (*PAGELLUS ACARNE*) EN LOS POBLAMIENTOS DE PECES DEMERSALES DE AGUAS SOMERAS FRENTE A LAS COSTAS DEL SUROESTE DE PORTUGAL. – Los efectos de un incremento en la dimensión de la malla del copo desde 65 a 70 y 80 mm, así como un cambio en su configuración entre malla de diamante de 65 mm y malla cuadrada de 65 mm han sido evaluados sobre la selectividad por talla del arte de arrastre para jurel (*Trachurus trachurus*), merluza europea (*Merluccius merluccius*) y aligote (*Pagellus acarne*) en los poblamientos de peces demersales de aguas someras frente a la costa del suroeste de Portugal. El incremento del tamaño de la malla ha tenido un efecto pequeño pero significativo sobre la selectividad por tamaños de las tres especies, mientras que el cambio de la configuración de la malla conlleva un incremento mucho más pronunciado en los parámetros de selectividad. En el caso del jurel, las estimaciones de la L_{50} oscilan entre 14.4 y 16.0 para los copos con malla de diamante; valores que se encuentran próximos a la talla mínima de desembarco de 15 cm. Para la merluza, la L_{50} estimada ha sido 17.0 y 18.3 cm para los copos de malla de diamante de 70 y 80 mm respectivamente, mientras que para el aligote la L_{50} estimada ha sido 13.9 cm para el copo de malla diamante de 80 mm. Los parámetros anteriores se encuentran por debajo de la talla mínima de desembarco de las dos especies (merluza: 27 cm; aligote: 18 cm). Las estimaciones de los parámetros correspondientes al copo de malla cuadrada han sido 21.9, 32.4 y

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19.6 cm para las tres especies respectivamente, con pérdida de un alto porcentaje (76%) de jurel por encima de la talla mínima de desembarco. En todos los copos analizados, la retención observada se ha expresado como una función de la relación perímetro máximo del pez/perímetro de la malla, lo cual permite un mejor entendimiento del proceso de selección de las especies estudiadas. Las estimaciones de parámetros de selectividad del jurel y de la merluza se han comparado igualmente con los obtenidos para estas especies en 1993 en aguas del sur de Portugal por Campos *et al.* (2003) en donde se capturan como *by-catch* en la pesquería de crustáceos.

Palabras clave: selectividad en el copo, dimensión de malla, configuración de malla, relación longitud/perímetro, by-catch, *Trachurus trachurus, Merluccius merluccius, Pagellus acarne.*

INTRODUCTION

The horse mackerel *Trachurus trachurus*, the axillary seabream *Pagellus acarne* and the European hake *Merluccius merluccius* are three commercially important species of the shallow ground fish assemblage of southern Portuguese waters (Gomes *et al.*, 2001). A number of other commercially valuable species, including seabreams and cephalopods, as well as some species with no commercial value and therefore discarded, are also included in this group. This assemblage extends over the southwest and southern continental coasts of Portugal at depths to approximately 120 m, and is exploited by the coastal bottom finfish trawling fleet. A total of 14 licensed fishing vessels are registered within this area, for which the legal cod end mesh size is 65 mm.

There are no studies quantifying the discard rates for the finfish trawlers fishing off the south west coast. However, mean discard rates per trip of 62% were estimated for the bottom finfish trawlers operating off the south coast in 1995-96 (Borges *et al.*, 2001), which target the same groundfish assemblage. The main reasons identified for discarding were the low or null commercial value of some species such as the longspine snipefish *Macroramphosus scolopax*, while for commercially valuable species most discards consisted of undersized fish.

Given scientific evidence pointing to overfishing of most demersal stocks in region 3, in which the Portuguese continental coast is included, the increase in cod end mesh size from 65 to 80 mm was proposed by the EC in 1991, but not subsequently adopted. Following this proposal, an evaluation of the consequences of increasing the cod end mesh size and changing mesh configuration was carried out by the Portuguese Institute for Fisheries and Sea Research - IPIMAR in the bottom trawl fishery off the south-west coast of Portugal. In the present study, some of the results obtained are presented for the horse mackerel, the European hake and the axillary seabream and are compared to those obtained for the first two species (Campos *et al.*, 2003) when captured as a by-catch in the crustacean fishery off the south coast.

MATERIAL AND METHODS

Data collection

The data in this paper were collected between 9 and 20 May 1992 off the south-west coast of Portugal on board the R/V “Noruega”, a stern trawler of 47.5 m length and 1500 HP belonging to IPIMAR. A total of 28 hauls (Fig. 1) carried out during daylight hours at depths of 45 to 100 m approximately, the depth range normally exploited by the finfish fleet, were chosen from a total of 42 valid hauls between Sesimbra and Arrifana. Haul duration was one hour for all hauls, at a constant trawling speed of about 3.5 kn. Three diamond mesh cod ends of 65 mm (8 hauls), 70 mm (5 hauls) and 80 mm (8 hauls) nominal mesh size and a square mesh cod end of 65 mm mesh size (7 hauls) were tested.

The trawl used in the experiments is similar to the one quoted as FGAV019 in Leite *et al.* (1990). Changes introduced in the latter gear design mainly concerned a general increase in the mesh size of the different panels, while maintaining the same overall dimensions. The gear was made of polyethylene, was approximately 47 m long (excluding cod end), and had a circumference of 566 meshes of 140 mm at the footrope level. It was rigged with a 55.4 m length footrope made of 18 mm steel cable covered with 24 mm polyethylene, 25 m sweeps with 22 mm diameter, 16 m legs of steel of 16 mm diameter, and steel otter boards of 4.3 m^2 and 650 kg.

Trawl geometry was recorded using Scanmar acoustic equipment, including depth, height, spread and trawl speed sensors. Vertical opening was about 3.1 m, and wing end and door spread 26.5 and 71.0 m respectively, at 3.5 kn.

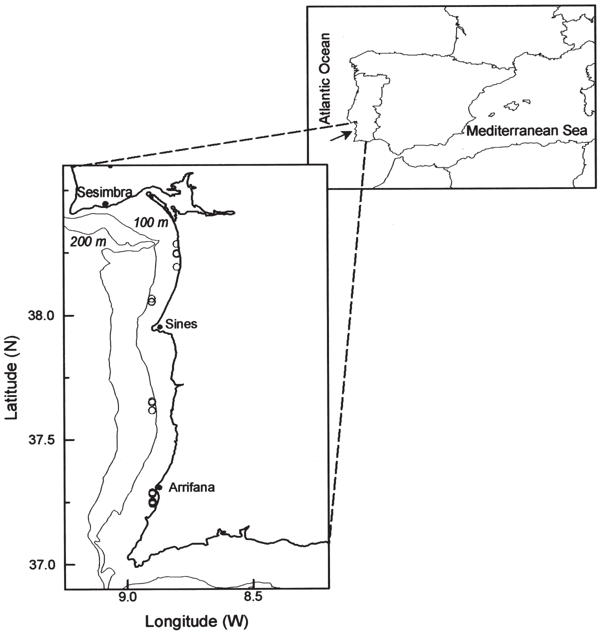

Fig. 1. – Location of selectivity hauls.

Cod end dimensions are shown in Table 1 for the four cod ends used. All cod ends were made of 2.5 mm single braided polyethylene, except for the square mesh cod end for which 2.0 mm twine was used. Cod end effective mesh sizes were measured during the surveys as the inside stretched mesh size using a calliper, due to the unavailability of an ICES gauge as recommended by Pope *et al.* (1975). The perimeter (given by number of meshes round times mesh size) of the diamond mesh cod ends was kept constant in order to achieve a similar mesh opening in all the experimental cod ends, since this is a variable which can affect selectivity to a large extent (Robertson and Ferro, 1988; Reeves *et al.*, 1992; Galbraith *et al.*, 1994). Due to their particular shape, square meshes always have the same (maximum) opening. Although selection factors (SF = L_{50}/mesh size) were calculated using the effective mesh size value, for practical reasons the nominal value will be referred to throughout.

The covered cod end method (Pope *et al.*, 1975) was used to assess escapement from the cod ends. The cover was made of single twisted PA 20 mm mesh size and 1.5 mm twine thickness. In order to minimise the possible masking effect of cod end meshes, the general dimensions of the covers were 1.5 times the width and the length of the cod ends, as proposed by Stewart and Robertson (1985) for covers when large catches are not expected.

After hauling up, catches from both the trawl cod end and cover were handled separately on board and weighed. Identification was almost always carried out to the species level and the weights registered for each species, both for the cod end and the cover. Total length was measured to the centimetre below for commercially valuable fish species. The whole catch was measured in all hauls for hake, captured in lower quantities, while horse mackerel and axillary seabream were sub-sampled in some of the hauls. In this case random samples were taken from the cod end, the cover or both, and the length class frequencies were then estimated by scaling up the sub-sampled frequencies by the ratio of the total weight to the sub-sample weight.

In order to determine girth/length relationships, maximum girth (unconstricted) and total length were measured, to the millimetre, in samples of 1017 individuals for horse mackerel, 260 for hake and 534 for axillary seabream.

Selectivity analysis

The probability r(l) that a fish of length l is retained, given that it entered the cod end, was modelled by means of the logistic selection curve

$$\mathrm{r}(l) = \frac{\exp(v_1 + v_2 l)}{1 + \exp(v_1 + v_2 l)}$$

where $\hat{v} = (v_1\ v_2)^{\mathrm{T}}$ is the maximum likelihood estimator of the vector of selectivity parameters. Estimation of $\hat{v}$ and the respective variance matrix R

TABLE 1. – Details of cod ends. Standard errors are in brackets; D, diamond mesh; S, square mesh.

Cod end mesh size (mm) Nominal	65D	70D	80D	65S
Measured	63.5 (1.54)	69.4 (2.26)	79.2 (1.74)	63.3 (1.90)
Nº of measurements	100	100	50	50
Dimensions (nº of meshes)				
width	115	106	93	64*
length	154	143	125	308*

* number of bars

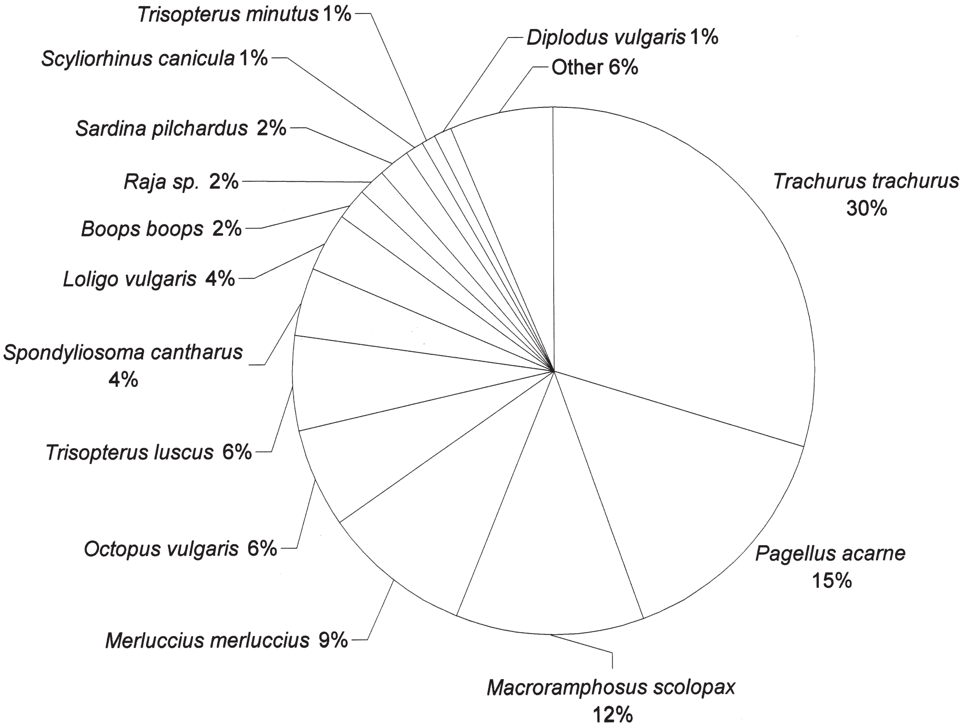

Fig. 2. – Species composition by weight, in cod end + cover (all hauls combined).

are described in Fryer (1991) and Millar and Fryer (1999).

For all the species in study, $\hat{v}$ was estimated based on the total number of individuals for each length class across all hauls within the same cod end, since the number of hauls for which the selectivity could be separately estimated was too low to estimate mean curves taking into account between-haul variation following the methodology of Fryer (1991). The selectivity parameters were estimated using the software CC 2000 (*ConStat*, DK).

A likelihood ratio test (McCullagh and Nelder, 1991) was carried out in order to determine whether the selection curves estimated for the different cod ends were statistically different from each other. In the present case, the ln-likelihoods resulting from fitting independent selection curves for each pair of contiguous mesh sizes were summed up, then a single curve was fitted to the data of both mesh sizes and the corresponding ln-likelihood was assessed.

$W^2 = 2 *$ [ln-likelihood (mesh size A) + ln-likelihood (mesh size B) - ln-likelihood (mesh size A + mesh size B)] is approximately $\chi^2_{(\alpha,\,\mathrm{dof})}$, where dof is given by the change in the number of parameters estimated when fitting the curves, if the null hypothesis, H_0, of no differences between curves is correct.

RESULTS

Horse mackerel was the most abundant species, together with the axillary seabream representing 45% of the total biomass in the catches (cover + cod end, Fig. 2), followed by the longspine snipefish *Macrorhamphosus scolopax,* a species with no commercial value that is discarded (12%), and by the European hake with 9%. Cephalopods and other seabreams accounted for 10 and 7% respectively of the total biomass.

Horse mackerel (*Trachurus trachurus*)

Horse mackerel was captured in large numbers within a length range of 6 to 34 cm approximately, with the mode at 17 cm, although the vast majority of the catches were found to be included in a much narrower range of 15 to 20 cm, for all mesh sizes (Fig. 3). In the 70D codend mesh size, where a higher proportion of larger individuals was caught, a second mode can be noticed at 22 cm. Fig. 4 shows the selectivity curves plotted together with the observed retention values in all mesh sizes. The 65 and 70 mm diamond mesh curves are almost coincident, the L_{50} estimates being 14.4 and 14.7 cm while the SRs were 3.3 and 2.9 cm respectively (Table 2). These

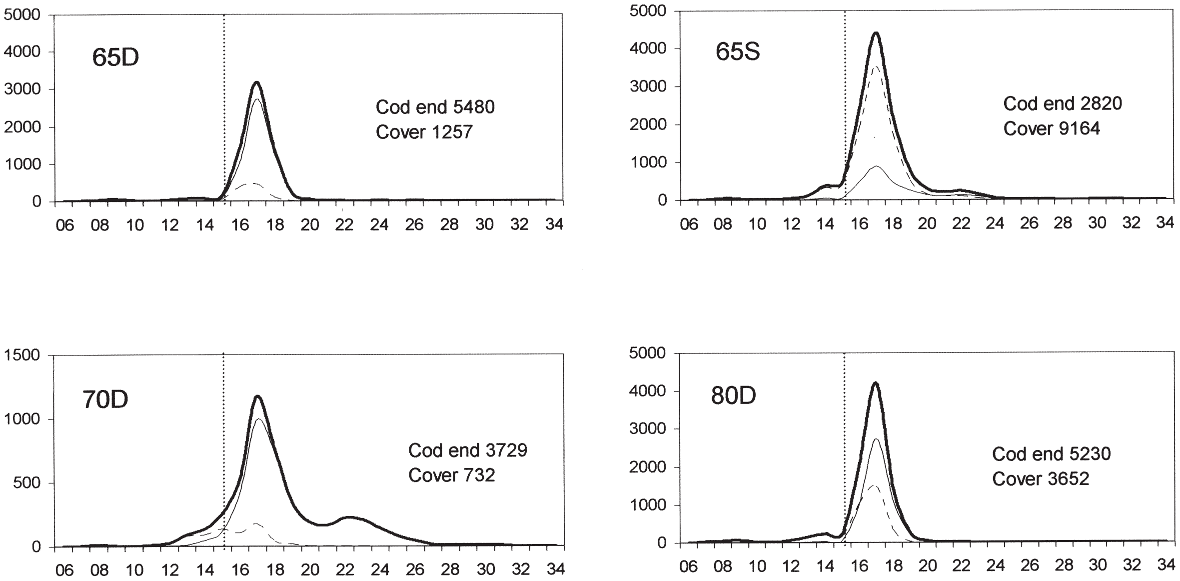

Fig. 3. – *Trachurus trachurus* (horse mackerel). Size structure of the populations that entered the diamond cod ends (D) and the square mesh cod end (S). X-axis – length (cm). Y-axis – numbers. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers. Dotted vertical line indicates the minimum landing size MLS.

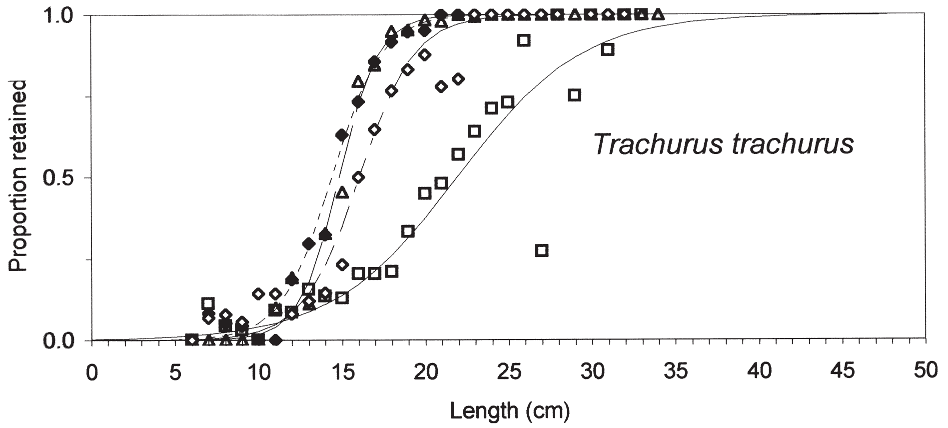

Fig. 4. – Selectivity curves for *Trachurus trachurus* (horse mackerel) based on pooled data, together with observed retention in the four cod ends. —- 65D; - - - 70D; - · - · - 80D; — 65S. Observed retention is expressed as black lozenges (65D), triangles (70D), white lozenges (80D) and squares (65S).

figures indicate that a 5 mm increase from the currently used mesh size of 65 mm has virtually no consequences in improving cod end selectivity. When the 80 mm diamond mesh was used, the L_{50} increased to 16.0 cm, while the selection range was 3.7 cm, slightly higher than for the other diamond mesh cod ends. If the selection factors are examined, a decrease is noticeable with the increase in mesh size from 2.3 to 2.1 and 2.0, indicating that horse mackerel did not make use of the greater escapement areas made possible by larger mesh sizes. On the other hand, the selectivity was much higher for the 65S cod end, as shown by the L_{50} estimate of 21.9 cm and SF of 3.8, while the SR estimate of 8.3 cm is also considerably higher.

The percentage of undersized horse mackerel that was retained is relatively low in all mesh sizes, about 20% for the 65 and 70D diamond cod ends, dropping to 11-12% when the mesh size is increased to 80 mm or the square mesh configuration is adopted (Table 2). However, the fraction of undersized individuals that entered the cod end was extremely low in all cod ends (4 to 7% of the total numbers) and estimation of the left branch of the selection curves was based on a low number of individuals, except for the 65S cod end. Conversely, while the losses of fish above MLS are about 15% for the smaller mesh size cod ends, they increase significantly for the 80D and 65S cod ends (37 and 76% respectively).

TABLE 2. – Selectivity parameter estimates for the three species in study in diamond meshes (D) and square mesh (S).The numbers in cod end and cover below and above the minimum landing size (MLS) are shown. v_1 and v_2 are the estimated selectivity parameters; R, the respective variance matrix; L_{25}, L_{50} and L_{75}, lengths at 25, 50 and 75% retention respectively; CI, confidence intervals for L_{50} and SR.

	Trachurus trachurus				*Merluccius merluccius*				*Pagellus acarne*			
Selectivity estimates	65D 8 hauls	70D 4 hauls	80D 6 hauls	65S 7 hauls	65D 8 hauls	70D 4 hauls	80D 8 hauls	65S 6 hauls	65D 8 hauls	70D 5 hauls	80D 8 hauls	65S 7 hauls
Retained												
<MLS	55	62	75	80	1527	380	1267	54	1479	87	1084	353
>=MLS	5425	3667	5155	2740	346	90	327	54	736	654	412	1614
Escapees												
<MLS	233	229	590	591	97	82	288	620	279	10	714	2229
>=MLS	1024	503	3062	8573	4	0	2	123	8	22	76	1179
v_1	-9.519	-11.269	-9.487	-5.802	-	-12.635	-9.547	-8.662	-	-	-4.155	-12.054
v_2	0.662	0.765	0.592	0.265	-	0.742	0.522	0.267	-	-	0.299	0.615
R_{11}	0.255	0.651	0.408	0.160	-	2.553	0.471	0.648	-	-	0.215	1.425
R_{12}	-0.0153	-0.0396	-0.0243	-0.0090	-	-0.1397	-0.0226	-0.0243	-	-	-0.0135	-0.0761
R_{22}	0.00090	0.00243	0.00146	0.00051	-	0.00770	0.00110	0.00090	-	-	0.00099	0.00412
L_{50} (cm)	14.4	14.7	16.0	21.9	-	17.0	18.3	32.4	-	-	13.9	19.6
L_{25} (cm)	12.7	13.3	14.2	17.8	-	15.5	16.2	28.3	-	-	10.2	17.8
L_{75} (cm)	16.0	16.2	17.9	26.1	-	18.5	20.4	36.5	-	-	17.6	21.4
CI L_{50} (cm)	14.2-14.6	14.5-15.0	15.9-16.2	21.1-22.8	-	16.5-17.5	17.9-18.7	30.6-34.2	-	-	13.4-14.4	19.1-20.1
SR (cm)	3.3	2.9	3.7	8.3	-	3.0	4.2	8.2	-	-	7.4	3.6
CI SR (cm)	3.0-3.6	2.5-3.3	3.2-4.2	6.8-9.8	-	2.2-3.7	3.6-4.7	6.3-10.2	-	-	5.8-8.9	2.8-4.4
SF	2.3	2.1	2.0	3.5	-	2.5	2.3	5.1	-	-	1.8	3.1
Deviance	17.1	63.5	70.2	103.6	-	8.9	16.2	16.0	-	-	18.5	276.2
df	21	27	24	26	-	30	32	18	-	-	16	22
p-value	0.71	0.00	0.00	0.00	-	1.00	0.99	0.59	-	-	0.30	0.00

European hake (*Merluccius merluccius*)

Hake were captured in much lower numbers than the previous species, ranging in size from approximately 15 to 40 cm (Fig. 5). In the 65 mm diamond and square mesh cod ends a modal class can be observed at 22 cm, while in the 80 mm diamond cod end the distribution tends to be bimodal, with two close modes of similar abundance (21 and 24 cm). In the 70 mm cod end, where the size distribution is somewhat irregular, a higher proportion of smaller individuals was captured, showing a first mode at 18 cm and a second one, which is less distinct, at 22 cm.

Selectivity parameters were not estimated for the 65D cod end since the observed retention proportions were mostly concentrated above 0.7 (Fig.6). For the 70 and 80D cod ends the L_{50} estimates were very similar, 17.0 and 18.3 cm respectively, while for the 65S cod end the estimate was much higher (32.4 cm). The SR estimates were also lower for the 70 and 80D cod ends (3.0 and 4.2 cm respectively),

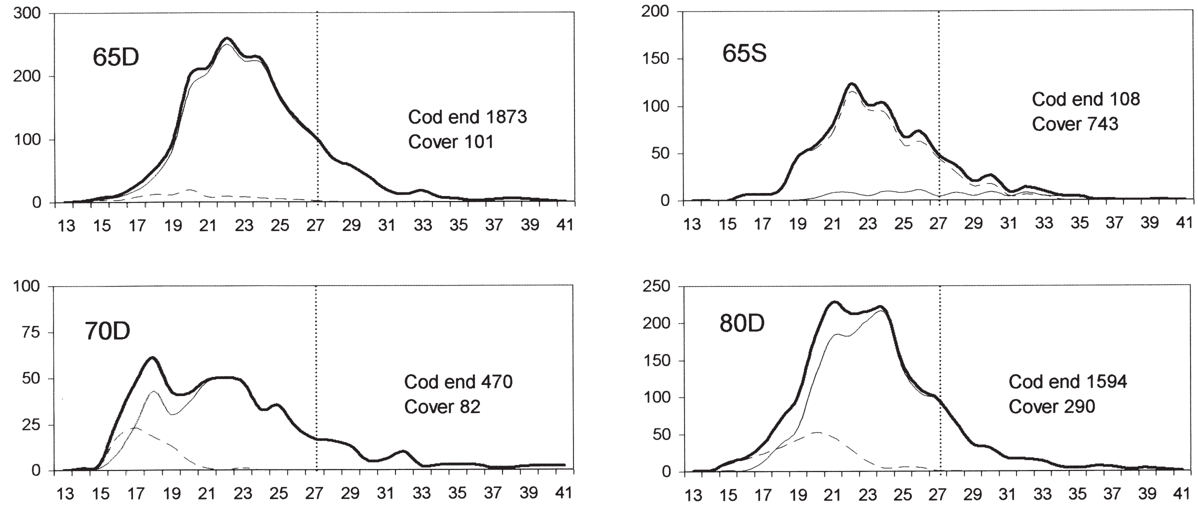

FIG. 5. – *Merluccius merluccius* (European hake). Size structure of the populations that entered the diamond cod ends (D) and the square mesh cod end (S). X-axis – length (cm). Y-axis – numbers. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers. Dotted vertical line indicates the minimum landing size MLS.

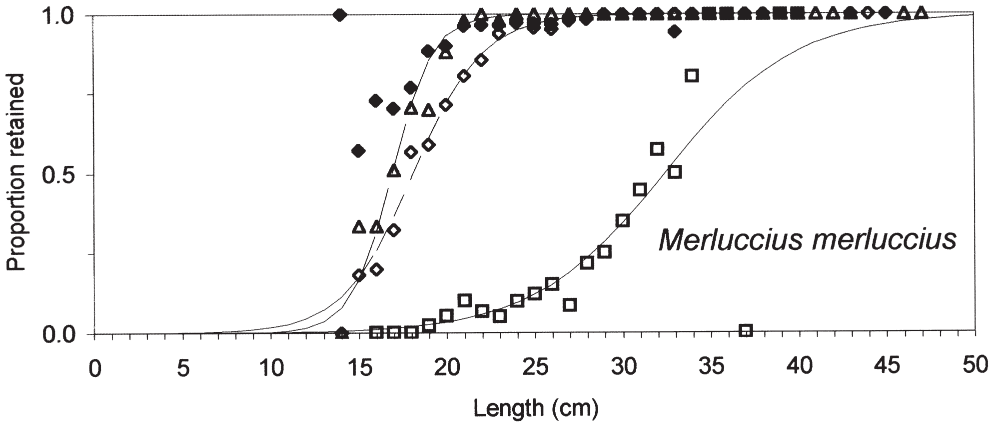

FIG. 6. – Selectivity curves for *Merluccius merluccius* (European hake) based on pooled data, together with observed retentions in the four cod ends. ---70D; -·-·-80D; —— 65S. Observed retention is expressed as black lozenges (65D), triangles (70D), white lozenges (80D) and squares (65S).

when compared to the square mesh cod end estimate of 8.2 cm (Table 2). This difference in SR values, resulting from a much sharper slope for the diamond mesh codends, denotes the very different selective properties of the two mesh configurations.

The 65S curve was estimated based on an observed range of retention values that do not cover the interval between 0 and 1 (Fig. 6). The selectivity estimates are based mainly on the length classes from 15 to 30 cm, where escapement was high, since catches of larger individuals were extremely rare. This data structure contributed to the much higher estimate of SR, as well as to the wider confidence intervals for L_{50} and SR when compared to diamond cod ends.

The retention of undersized fish (Table 2) was around 80% in the 70 and 80 mm diamond cod ends, while in the 65 mm square mesh cod end most small fish escaped but a loss of 70% was observed for commercial sized catches.

Axillary seabream (*Pagellus acarne*)

Axillary seabream ranging from approximately 12 to 35 cm were captured (Fig.7). For the 65 and 80 mm diamond mesh cod ends the greater part of the catches were concentrated in the length classes from 14 to 17 cm. The size distributions are clearly bimodal, with the first mode, by far the most abundant, at 15 cm, while a second one, with much lower numbers of individuals, is found at 18 cm. For the other two cod ends the size structure of the catch differed substantially, with the capture of a higher fraction of bigger individuals from 17 to 22 cm. While the mode remained at 15 cm in the 65S cod end, in

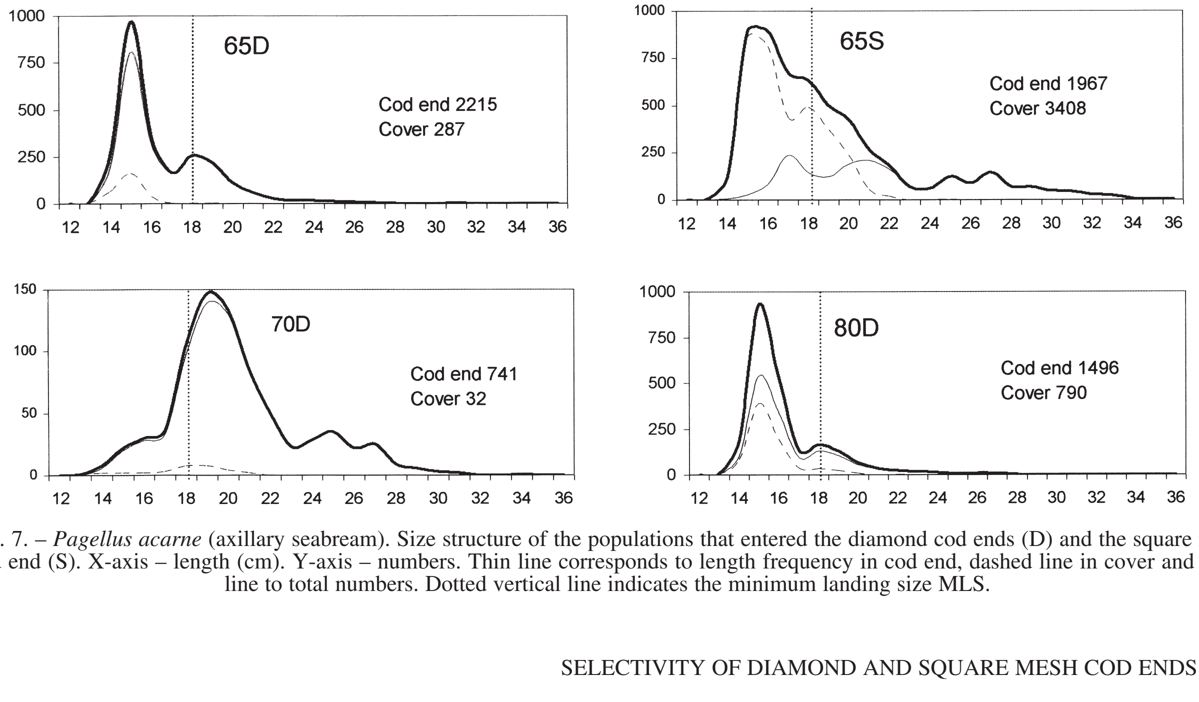

FIG. 7. – *Pagellus acarne* (axillary seabream). Size structure of the populations that entered the diamond cod ends (D) and the square mesh cod end (S). X-axis – length (cm). Y-axis – numbers. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers. Dotted vertical line indicates the minimum landing size MLS.

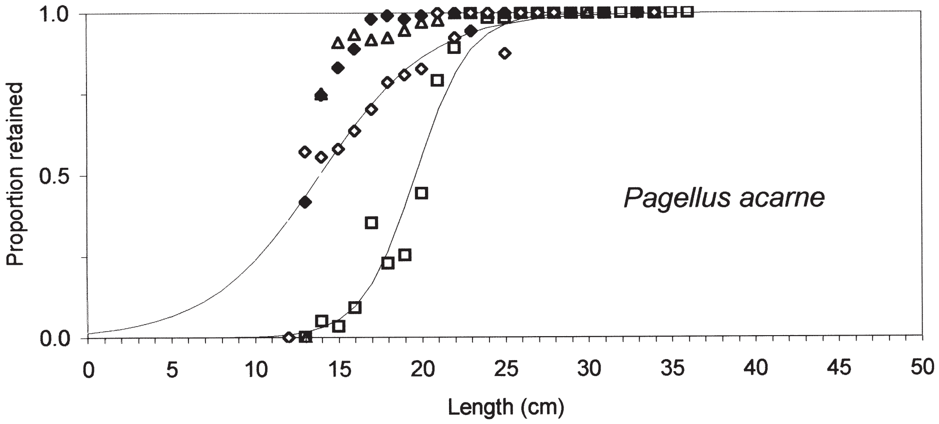

Fig. 8. – Selectivity curves for *Pagellus acarne* (axillary seabream) based on pooled data, together with observed retentions in the four cod ends. - · - · - 80D; — 65S. Observed retention is expressed as black lozenges (65D), triangles (70D), white lozenges (80D) and squares (65S).

the 70D cod end there was a shift towards 19 cm, together with lower abundance of the smaller individuals from 14 to 16 cm.

It should be noted that although the catches in the 70D cod end were lower for all species in study, which can partly be attributed to the lower number of hauls carried out with this mesh size, they are particularly low for the axillary seabream.

For both the 65 and 70D cod ends even the smaller length classes were almost completely retained, and therefore selectivity estimates are not presented for these cod ends, while for the 80D and 65S cod ends (Fig. 8) the L_{50} estimates were 13.9 and 19.6 cm and the selection ranges 7.3 and 3.6 cm respectively (Table 2). Similarly to what was observed for the other species, the use of a square mesh cod end resulted in a significant improvement in the selectivity, as shown by the difference in the respective selection factors (1.8 and 3.6).

In the 80 mm diamond cod end a retention of 60% was observed for undersized fish, while the use of the square mesh resulted in the loss of 42% of all fish above the MLS.

The results of the likelihood ratio test for comparing the selection curves of pairs of mesh size/configuration cod ends fitted for each species are given in Table 3. At the 0.01 level of significance, the only case for which the null hypothesis of no difference between mesh sizes was accepted was for horse mackerel, for which the 65D curve was compared to the 70D, while for all the other pairs of mesh sizes significant differences were always found (p-value < 0.001).

TABLE 3. – Results of the likelihood ratio test comparing pairs of selection curves.

	mesh sizes	significance
Trachurus trachurus	65D/70D	0.041
	70D/80D	<0.001
	80D/65S	<0.001
Merluccius merluccius	70D/80D	<0.001
	80D/65S	<0.001
Pagellus acarne	80D/65S	<0.001

Girth selectivity

The maximum girth/total length relationships estimated for the three species are presented in Table 4 and plotted in Figure 9. For horse mackerel and hake these relationships are very close to those estimated in June 1999 by Fonseca *et al.* (unpublished data) for the west coast of Portugal, while for the axillary seabream it is close to that reported by Santos *et al.* (1995) for the south coast. For all species girth is highly correlated with length, as shown by the high values of the coefficient of determination (see Table 4). For the same length, the maximum

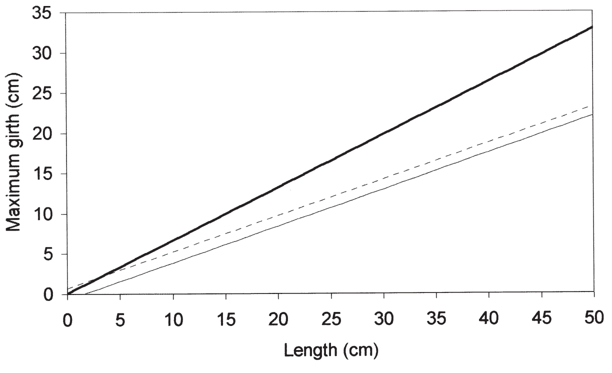

FIG. 9. – Maximum girth-total length relationships for the species in study. Thin line – *Merluccius merluccius* (European hake); dashed line – *Trachurus trach*urus (horse mackerel); thick line – *Pagellus acarne* (axillary seabream).

TABLE 4. – Maximum girth-total length relationships.

	G_{max}	r^2	N	L_t (cm)
Trachurus trachurus	$0.449 * L_t + 0.713$	0.865	1017	14.2 - 33.8
Merluccius merluccius	$0.455 * L_t - 0.732$	0.937	260	16.0 - 75.0
Pagellus acarne	$0.656 * L_t + 0.081$	0.947	534	15.5 - 34.5

girth attains its lowest value for hake and the highest one for the axillary seabream. In addition, a higher increase in girth with length is observed for axillary seabream than for the other two species, which explains the lower SR estimate in the square mesh cod end as a result of a steeper curve.

Considering the high correlation between the two dimensions it was possible to plot the retention proportion versus G_{max}/mesh perimeter (where G_{max} was directly obtained from the retention-at-length plots), without much concern for the fact that with such a procedure the girth variance for a given length is not taken into account (Fig. 10). This type of plot allowed the direct comparison of the retention proportions in all cod ends for the three species by bringing the corresponding maximum girths to the same scale.

DISCUSSION

The three species studied are considerably different from the morphological point of view and in size range, and consequently differences are expected in their behaviour towards the fishing gear in general and to the increase in cod end mesh size or change in mesh configuration in particular.

Despite these differences, common general selection patterns can be identified for horse mackerel and hake. Both these species have diamond mesh cod end size selection curves with much steeper slopes than those found for the square mesh cod end, while for the axillary seabream the opposite can be observed. However, common selection patterns do not mean similar selectivity. In fact, there is a large between-species difference in how horse mackerel and hake of the same length use the opportunity of escape offered by an increase in mesh size or a change in mesh configuration. For the same mesh size, the horse mackerel has a consistently higher retention (lower selectivity) than hake of the same length. This difference is particularly striking when the change in mesh configuration is considered. Similar considerations can apply to the retention for axillary seabream when compared to hake.

The explanation for the differences in size selectivity found for the three species in study is not

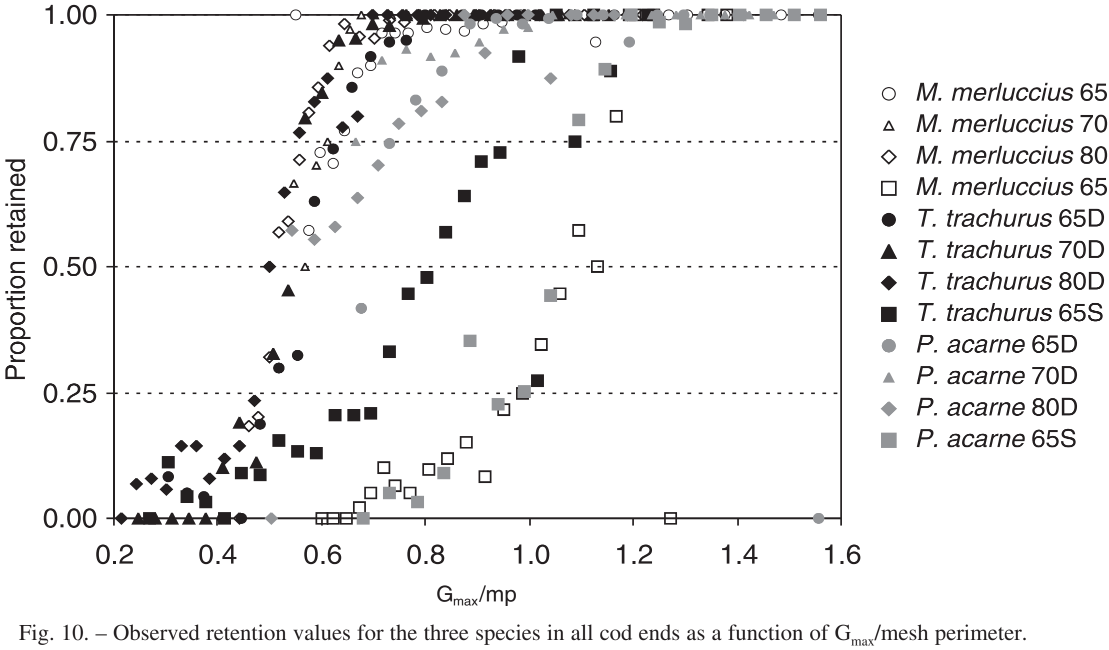

Fig. 10. – Observed retention values for the three species in all cod ends as a function of G_{max}/mesh perimeter.

straightforward. Since the work of Baranov (1948), it is widely assumed that the probability of retention is primarily determined by the relationship between the body shape and mesh opening, although it is usually expressed as a function of body length, which is easier to measure. Considering that in these data length was highly correlated with maximum girth, selectivity-at-length was converted into selectivity-at-girth, looking for a better explanation of the selection patterns observed, since girth gives a better approximation to fish shape.

If the maximum body girth alone was the critical dimension for these species when attempting to escape through the meshes, then it would be expected that fish of the same body girth escape from the same type of cod end (diamond mesh *vs.* square mesh) in a similar way, irrespective of the species. However, this was not observed, since it becomes evident that, for the same value of G_{max}/mp, escapement is lower for hake, increasing slightly for horse mackerel and more significantly for axillary seabream within the diamond mesh cod ends. The retention started at G_{max}/mp values of between 0.3 and 0.4, and attained 100% at $G_{max}/mp = 0.7$ for horse mackerel and hake, while for axillary seabream no individuals were captured with $G_{max}/mp < 0.5$, which corresponded to 50% retention, while full retention was achieved for individuals with $G_{max}/mp = 1$. The first two patterns are somewhat different from that found by Tokai *et al.* (1994) and Liang *et al.* (1999) for diamond cod ends in Japanese waters, in which the retention started at approximately G_{max}/mp of 0.5 and attained its maximum at 1.0 for most of the species studied.

The retention patterns are quite different for the square mesh cod ends, in which horse mackerel retention starts approximately at a G_{max}/mp of 0.4 and attains its maximum around 1.0, for a fish length of 26 cm corresponding to a girth equal to the mesh perimeter, while for hake and axillary seabream all fish with $G_{max}/mp < 0.8$ escaped and they could escape even at girths higher than the respective mesh perimeters, corresponding to fish lengths larger than 29 and 19 cm respectively.

This suggests that escapement through the cod end meshes has certainly depended to some extent on other factors besides the maximum girth, such as body shape and stiffness, swimming ability and reaction to the gear panels. Hake and axillary seabream can probably fit better to square meshes than horse mackerel due to the fact that their bodies are softer and more compressible, although their body proportions are somewhat different, particularly the hake which is more round-shaped. This feature probably contributes to explaining the higher retention for hake in the diamond cod ends when compared to the other two species. Differences in escape behaviour can also be responsible for part of the variability observed, with Figure 10 suggesting a more active escape behaviour for the axillary seabream. Although this hypothesis is subject to confirmation by direct observation of the catch process, it is in accordance with observations by Tokaç *et al.* (1998), who report heavy meshing of axillary seabream in cod ends that is compatible with active escape behaviour.

For horse mackerel, L_{50} estimates in this study are around the minimum landing size of 15 cm for the 65 and 70D cod ends, and slightly higher for the 80D. An acceptable balance between the retention of undersized individuals and the escape of commercial sized fish was therefore achieved with the smaller mesh sizes.

Both hake and axillary seabream L_{50} estimates for the diamond mesh cod ends are well below the MLS of 27 and 18 cm respectively. The difference is particularly high for hake (about 9/10 cm, for the 70 and 80 mm cod ends), resulting in extremely high retention of undersized fish. For the 65 mm square mesh cod end, the L_{50} (32.4 cm) is considerably higher than the MLS, thus allowing for the escapement of most of the small fishes but resulting in major losses of commercially sized individuals. For the axillary seabream, the L_{50} in the 80D cod end was 13.9 cm, with a high retention of undersized fish, while the use of the square mesh resulted in the loss of an appreciable fraction of fish above the MLS.

Previous results on selectivity for horse mackerel and hake can be found in Campos *et al.* (2003), where these species were captured as a by-catch in crustacean fishing grounds off the Potuguese south coast, at depths from 150 to 700 m, using diamond mesh cod ends of 55, 60 and 70 mm and a square mesh cod end of 55 mm. For horse mackerel, the SF was 3.1 and 3.9 in the 70D and 55S cod ends respectively, corresponding to L_{50} estimates of 21.9 and 21.7 cm. These latter values are similar to those obtained in the present study for the 65 mm square mesh, suggesting that the selectivity for horse mackerel in the finfish trawling is much lower than in the crustacean trawling. A similar situation, although less evident, is found for hake, for which there are previous data only for the 55 and 60 mm diamond mesh cod ends with a SF of 2.9, which is higher than the SFs of 2.5 and 2.3 estimated herein for the 70 and 80D cod ends.

These differences in selectivity for both species are certainly related to a large extent to the fact that distinct fish assemblages are exploited at different depth ranges. The observed differences in the overall catch composition, as well as in length composition, can explain part of the variability within the selectivity results. This is particularly valid for hake, for which differences in length composition were found between experiments, with a higher fraction of smaller fish together with a lower number of larger individuals being captured in the crustacean fishing grounds. For horse mackerel, a similar length distribution was observed in both experiments, although the catches by the finfish trawl were much higher.

Moreover, differences in the trawl design between experiments have most likely affected the cod end geometry and mesh opening in the diamond mesh cod ends, contributing to differences in selectivity. While the cod end perimeter was kept constant (and equal to the perimeter of the trawl rear panel) in order to ensure the same mesh opening within each trawl, it was different between trawls due to differences in trawl design, and differences in the cod end mesh opening, which were not controlled, probably occurred between experiments.

Another hypothesis for the explanation of the differences between experiments can arise from the experimental method itself. Since in the present experiments, unlike those for crustaceans in 1993 (Campos *et al*., 2003), no hoops were used in the cover, the eventual occurrence of a masking effect can be raised. However, as explained in previous section, the cover used was especially designed to prevent its collapse over the cod end. Furthermore, the analysis of selectivity data for the square mesh cod end showed that both hake and axillary seabream escaped through meshes at a girth higher than mesh perimeter, which is not in accordance with a masking effect.

Selectivity data for axillary seabream in Portuguese waters were obtained for the first time during the present experiments. However, Tokaç *et al.* (1998), in selectivity trials in the Aegean Sea using diamond and square mesh cod ends, reported higher selectivity for this species in the diamond cod ends (SF between 2.95 and 3.22, corresponding to L_{50} estimates of 10.61 to 14.16 cm), but at the same time found non-significant differences in selectivity between diamond and square mesh cod ends of the same mesh size. Once more, differences in selectivity between those data and data presented in this work could be related to differences in length composition and range of mesh sizes tested (smaller fish from 10 to 15 cm and cod end mesh sizes from 36 to 44 mm in their experiments), as well as differences between cod end material (polyamide versus polyethylene in the present work) and cod end geometry and mesh opening, particularly with respect to the diamond cod ends.

CONCLUSIONS

In conclusion, the results from the present study, although concerning only three of the many commercial species captured in the finfish trawl *métier*, are a good example of the difficulty in managing multi-species fisheries based simply on mesh size regulations.

It is suggested that, for horse mackerel, the most captured species during these experiments, the current minimum legal mesh size of 65 mm is adequate. On the other hand, data for hake and axillary seabream reveal a worrying scenario, since for both species even the increase of the minimum mesh size to 80 mm, while keeping the diamond configuration, is too small to prevent the capture of an extremely high proportion of fish below the respective MLSs.

The change in mesh configuration to 65 mm square mesh would lead to the escapement of a high percentage of horse mackerel larger than the MLS (about 76%), while for hake and axillary seabream the use of square mesh codends would contribute to a drastic decrease in the catch of undersized fish, but concurrently, there would be an unacceptable loss of fish of commercial size.

The different responses of the three species in relation to the change in mesh size or mesh configuration within this experiment can be associated with differences in morphology, swimming endurance and behaviour, while gear-dependent factors, such as cod end dimensions, twine thickness and construction, as well as operational factors, (trawling speed, catch size, etc.), can help to explain differences between experiments. Still, the relationship between body shape and mesh opening is a key factor, and the consequences of an increase in mesh opening by reducing the number of meshes round the cod end should be evaluated for Portuguese trawl fisheries. It is suggested that although maximum girth is a useful dimension to take into account in selectivity studies, it is still not the most adequate for the description of the selection process, since it does not express the fish shape in an accurate manner. A more realistic representation of the selection process would most probably be achieved by considering, as do Efanov *et al.* (1987) and Liang *et al.* (1999), a coefficient based on the relationship between the height and the width at the region of maximum girth, and its relation to mesh size and mesh opening.

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Size selectivity for four fish species of the deep groundfish assemblage off the Portuguese southwest coast: evidence of mesh size, mesh configuration and cod end catch effects

Aida Campos*, Paulo Fonseca, Victor Henriques

IPIMAR, Avenida de Brasília, 1449-006 Lisbon, Portugal

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Abstract

The effects were evaluated of an increase in cod end mesh size from 65 to 70 and 80 mm and change of mesh configuration from 65 mm diamond to 65 mm square mesh on the size selectivity of hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), four-spot megrim (*Lepidorhombus boscii*) and blue whiting (*Micromesistius poutassou*) captured on the upper continental slope off the Portuguese southwest coast, at depths from approximately 200–400 m. A number of individual hauls were analysed in the diamond mesh cod ends, for hake and blue whiting, and in the square mesh cod end, for horse mackerel, and mean selection curves were estimated for these cod ends taking into account between-haul variation. For the four-spot megrim, the selectivity estimates were based on pooled data for all the cod ends tested. Selectivity models are proposed for hake and blue whiting in which positive effects of both the increase in mesh size and in cod end catch were estimated for L_{50}, while SR was only affected by mesh size. For horse mackerel a positive effect of cod end catch was estimated for SR in the square mesh cod end. The selectivity was greatly affected by the change in mesh configuration for all species with the exception of the four-spot megrim, for which only mesh size was found to affect selectivity.

Keywords: Cod end selectivity; Mesh size; Mesh configuration; Between-haul variation; *Merluccius merluccius*; *Micromesistius poutassou*; *Trachurus trachurus*; *Lepidorhombus boscii*

1. Introduction

The upper slope of the Portuguese continental southern waters, including the southwest and south coasts at depths from 200 to 500 m approximately, is characterised by the presence of a deep groundfish assemblage (Gomes et al., 2001) dominated by the blue whiting *Micromesistius poutassou*, and comprising a number of commercial species such as the horse mackerel *Trachurus trachurus* and the European hake *Merluccius merluccius*, as well as other less-captured species with high commercial value. Although hake and horse mackerel are species that are also common in the shallow groundfish assemblage defined by the same authors for the continental shelf to a depth of approximately 120 m, the two assemblages are distinct in terms of species composition (Gomes et al., 2001). Furthermore, in several studies (Borges and Gordo, 1991; Murta and Borges, 1994; Cardador, 1995), length was found to be depth-dependent for horse mackerel and hake, with differences in terms of the length distributions of the continental shelf

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* Corresponding author. Tel.: +351-21-302-7163;
fax: +351-21-301-5948.
E-mail address: acampos@ipimar.pt (A. Campos).

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and the upper slope populations, suggesting that both species are found in the two assemblages at distinct stages of their respective life cycles.

Campos and Fonseca (2003) estimated the selectivity of diamond cod ends of 65 mm (the legal mesh size for finfish trawling), 70 and 80 mm and a square mesh cod end of 65 mm mesh size for the most abundant species of the shallow groundfish assemblage of the southwest coast, the horse mackerel, the European hake and the axillary seabream *Pagellus acarne*. In the present paper, the selectivity of the same cod ends was evaluated for the horse mackerel, the European hake, the blue whiting and the four-spot megrim *Lepidorhombus boscii* caught on the upper continental slope off the southwest coast between 200 and 400 m, allowing for a general characterisation of the selectivity in the deep groundfish assemblage and providing greater insight into the selectivity of hake and horse mackerel.

2. Data collection

These data were obtained within the scope of a research project carried out by the Portuguese Institute for Fisheries and Sea Research (IPIMAR) aiming at the evaluation of the consequences of an increase in the cod end mesh size and change in the mesh configuration from diamond to square mesh on trawl selectivity for commercial fish species of the Portuguese southwest coast. A total of 60 hauls were used in this study, carried out between 5 and 19 August 1992, covering a part of the southwest coast between Sines and Arrifana (Fig. 1) at depths from 200 to 400 m, using the R/V “Noruega”, a 47.5 m and 1500 HP stern trawler belonging to IPIMAR. All hauls had a duration of 1 h and were carried out during daylight hours, in stable weather and sea conditions using diamond mesh cod ends of nominal mesh sizes of 65 mm (13 hauls), 70 mm (18 hauls) and 80 mm (19 hauls) and a square mesh cod end of 65 mm mesh size (10 hauls). Each haul was carried out at a constant depth and at a trawling speed of 3.5 knots approximately, which is within the range of speeds in the finfish bottom trawl fishery.

The trawl used in the experiments was the same as that used by Campos and Fonseca (2003). It was made of braided polyethylene and was about 47 m long (excluding cod end), with a circumference of 566 meshes of 140 mm at the footrope level (Fig. 2). It was fitted with a 55.4 m length footrope made of 18 mm steel wire covered with 24 mm polyethylene cable, 25 m sweeps and steel otter boards with 4.3 m^2 and 650 kg.

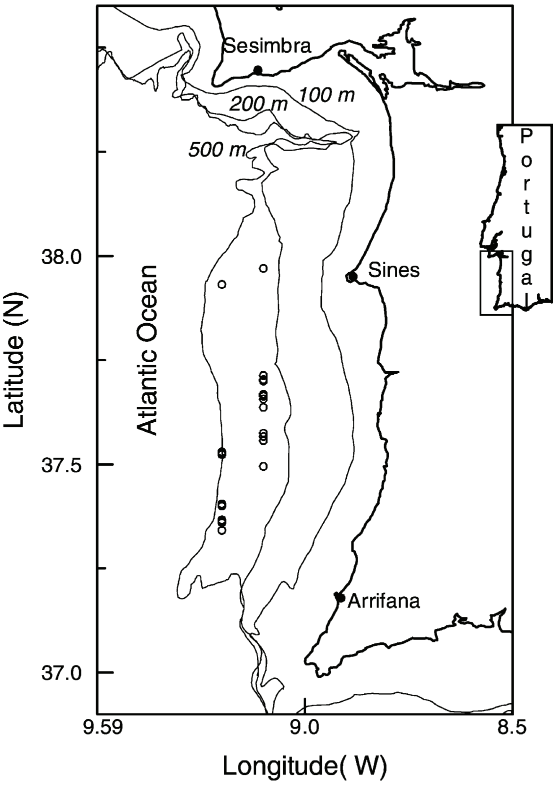

Fig. 1. Fishing area and hauls.

The characteristics of the different cod ends are given in Table 1. All cod ends were made of 2.5 mm braided polyethylene, except for the square mesh cod end where 2.0 mm twine was used. Due to the unavailability of an ICES gauge as recommended by Pope et al. (1975), the cod end effective mesh sizes were measured during the surveys as the inside stretched mesh size using a calliper. Since the mesh opening is a variable that affects selectivity to a large extent (Robertson and Ferro, 1988; Reeves et al., 1992; Galbraith et al., 1994), the perimeter of the diamond mesh cod ends (given by the number of meshes round times the mesh size) was kept constant in order to achieve a similar mesh opening throughout

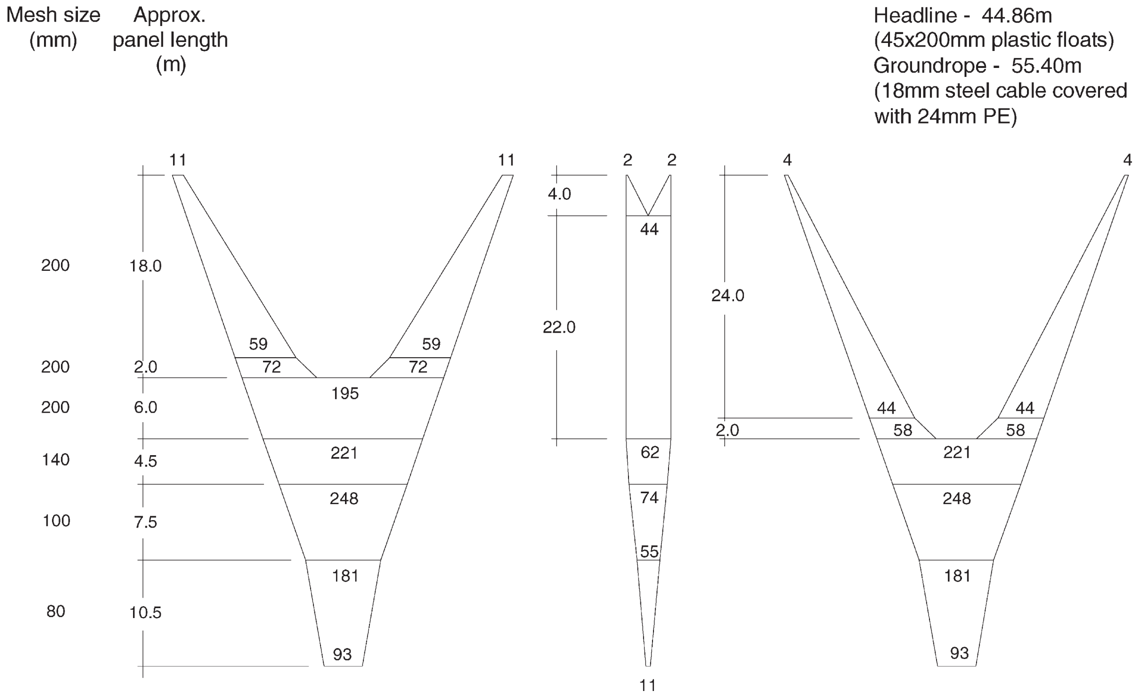

Fig. 2. Technical drawing for the trawl used.

Table 1
Details of cod ends[a]

	Cod end mesh size (mm), nominal			
	65D	70D	80D	65S
Measured	63.5 (1.54)	69.4 (2.26)	79.2 (1.74)	63.3 (1.90)
Number of measurements	100	100	50	50
Dimensions (number of meshes)				
Width	115	106	93	64[b]
Length	154	143	125	308[b]

[a] Standard errors are in brackets.

[b] Number of bars.

the experimental fishing trials. Selection factors were calculated using the effective mesh sizes, although for convenience the nominal value will be referred to in the text.

Trawl geometry and speed were recorded for most hauls using acoustic depth, height and spread sensors, and a speed sensor. Vertical opening was about 3.1 m, and wing end and door spread were 23.5 and 62.5 m, respectively, at 3.5 knots.

3. Experimental method

The experimental method used was the covered cod end (Pope et al., 1975; Wileman et al., 1996). To overcome an eventual masking effect of cod end meshes, the dimensions of the cover were 1.5 times the width and the length of the cod ends, according to the recommendations of Stewart and Robertson (1985) for covers where large catches are not expected. The cover

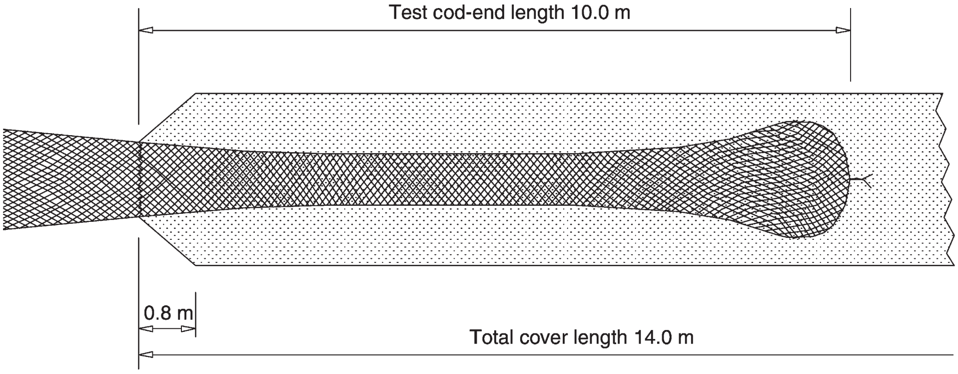

Fig. 3. Covered cod end.

was made of single twisted PA 20 mm mesh size and 1.5 mm twine thickness, and mounted over the cod ends as shown in Fig. 3.

After arrival on the deck, catches in the cod end and the cover were handled separately and weighed. Almost all taxa were determined to the species level and the respective weights registered. Total length was measured to the centimetre below for commercially valuable fish species and for blue whiting, the dominant species in most of the hauls. The whole catch of hake and four-spot megrim was always measured, while for horse mackerel and blue whiting random samples had to be taken in some of the hauls from the cod end, the cover or both. The length class frequencies were then estimated by scaling up the sub-sampled frequencies by the ratio of the total weight to the sub-sample weight.

4. Selectivity analysis

The probability $r(l)$ that a fish of length l is retained, given that it entered the cod end, was modelled, for individual hauls or, alternatively, for pooled data from all hauls within the same cod end, as a logistic curve

$$r(l) = \exp\frac{v_1 + v_2 l}{1 + \exp(v_1 + v_2 l)}$$

where $\hat{v} = (\,v_1 \quad v_2)^{\mathrm{T}}$, the maximum likelihood estimator of the vector of selection parameters, is approximately normally distributed with the expected value $\hat{v}$ and variance matrix $\hat{R}$ (Fryer, 1991).

Details on the estimation of $\hat{v}$ and R can be found in Fryer (1991). Correction for the effects of sub-sampling for individual hauls was carried out according to Millar (1994). Mean selectivity curves were estimated for all cod ends for which a number of individual hauls was fitted taking into account the between-haul variation of the selectivity parameters v_1 and v_2 according to Fryer (1991), while for the cases where no individual hauls could be fitted mean curves were estimated based on pooled data.

Fryer's model of between-haul variation was also used to model the selectivity data by estimating the individual contribution of other explanatory variables, besides those related to the cod end characteristics under study, that can play a role in the between-haul variation of the selectivity parameters estimated for these hauls.

A large number of all possible linear expressions of the selectivity parameters L_{50} and SR as functions of the variables mesh size and cod end catch were tested in this study. The choice of the models which best describe the data was based on the lowest value for Akaike's information criterion (Fryer and Shepherd, 1996).

The selectivity parameters for individual hauls were estimated using the software CC 2000 (ConStat, DK), while models which incorporate between-haul variation were adjusted using the software ECModel (ConStat, DK) that implements the methodology proposed by Fryer (1991).

A likelihood ratio test (McCullagh and Nelder, 1991) was carried out to evaluate if the pooled selection curves estimated for the four-spot megrim in the different cod ends were statistically different from each other. The ln-likelihoods resulting from fitting independent selection curves for each pair of contiguous mesh sizes were summed up, then a single curve was fitted to the data of both mesh sizes and the corresponding ln-likelihood assessed.

$W^2 = 2[\text{ln-likelihood}(\text{mesh size } A) + \text{ln-likelihood}(\text{mesh size } B) - \text{ln-likelihood}(\text{mesh size } A + \text{mesh size } B)]$ is approximately $\chi^2_{(\alpha,\text{df})}$, where df is given by the change in the number of parameters estimated when fitting the curves, if the null hypothesis H_0 of no differences between curves is correct.

4.1. Results

A total of 48 taxa, including fish (37), crustaceans (3), and cephalopods (8) were found in the catches of the group of hauls analysed.

Blue whiting was the dominant species, representing 44% of the total biomass in all cod ends (Fig. 4), followed by the boarfish *Capros aper* (28%) and the horse mackerel (14%). Hake represented only 4% of the total catch in these hauls, while all the other species, including the four-spot megrim, were captured in quantities that did not exceed 1% of the total catch.

4.2. European hake

Hake ranged from approximately 10–70 cm, although the majority of the fish were from 10 to 27 cm in all mesh sizes (Fig. 5). The length frequency distributions were bimodal, with a major peak at 19 cm and a minor one at 12 cm. A small proportion of the catches in all cod ends consisted of larger individuals between 27 and 70 cm, for which there is no distinct mode.

The number of individuals that entered the 65S cod end was much lower than in the other cod ends, in part due to the lower number of hauls (10 hauls) carried out with this mesh size. The selective properties of this cod end are well evident when compared to the others, allowing for almost total escapement of hake smaller than 27 cm.

A summary of hauls and catches is given in Table 2. Only 10 hauls were used in the analysis of between-haul variation, carried out with the 65 and 70 mm diamond mesh cod ends (five hauls in each cod

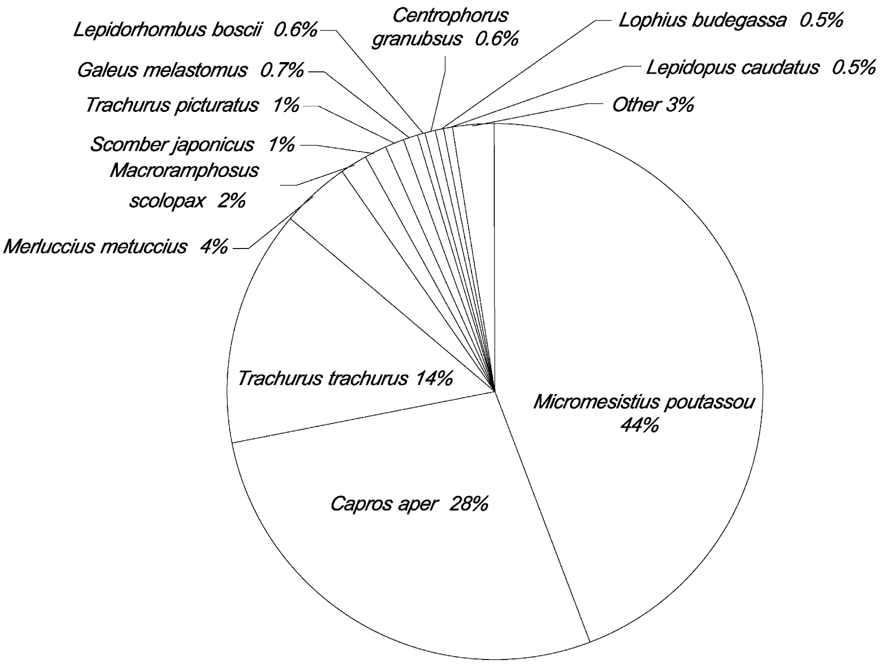

Fig. 4. Species composition by weight in cod end + cover, corresponding to a total catch of 15,674 kg in 60 hauls.

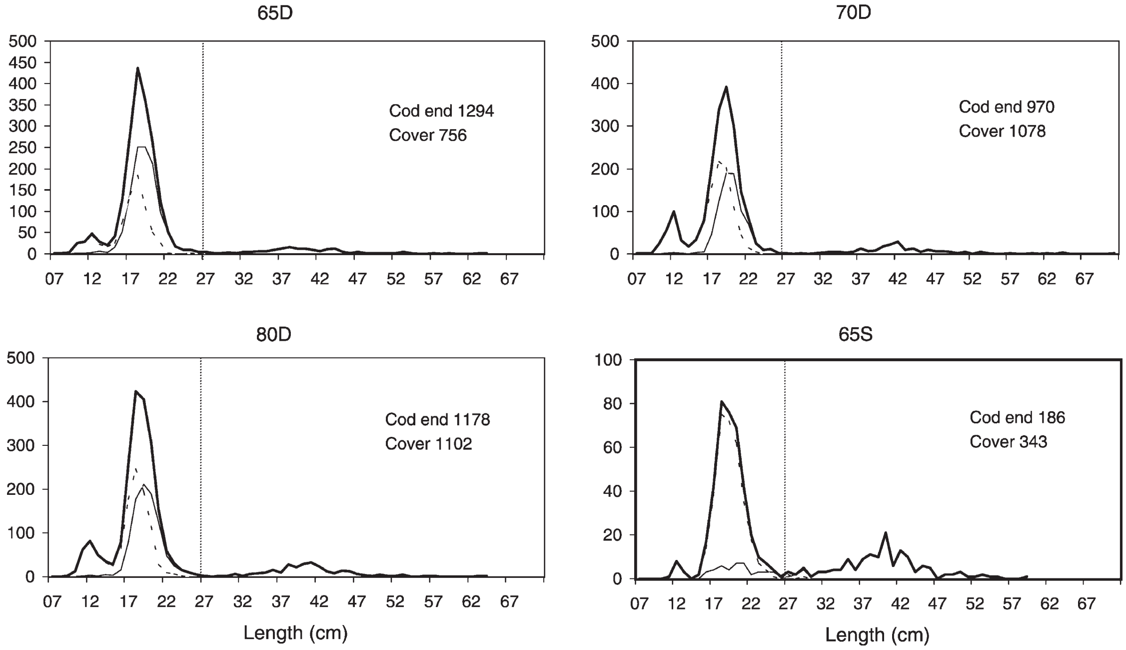

Fig. 5. European hake. Size structure of the populations that entered the different cod ends. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers. Vertical line MLS.

end), even though hake were caught in a total of 13 and 18 hauls, respectively. The reason for this is that hake were poorly represented in most of the hauls. However, the proportions of individuals included in the analysis (summed over all the individual hauls analysed) to the total number of individuals captured (Table 2) were relatively high, 79 and 58%, respectively. In the 80D and 65S cod ends the data structure did not allow for the estimation of the selectivity on a haul-by-haul basis.

Selectivity estimates are given in Table 3, where the parameters v_1 and v_2 of the fitted logistic curves are shown for all individual hauls and mean curves, together with the respective variance–covariance matrix R_i which estimates within-haul variation in these parameters. L_{50} estimates for the mean curves (Fryer and pooled) are similar for the 65 and 70D cod ends, with the estimates for pooled data being slightly lower (1 cm) than those obtained taking into account between-haul variation. For the pooled data an increase in L_{50} from 17.0 to 19.2 cm can be observed when mesh size increases from 65 to 70D but a decrease to 18.8 cm occurs when the 80 mm cod end is considered. On the other hand, L_{50} estimated for the 65 mm square mesh cod end is 25.0 cm, showing the much higher selective properties of this cod end. The correspondent estimates for SR are 5.2, 3.9 and 4.4 cm in the diamond mesh cod ends, and 5.6 cm in the square mesh cod end. SR estimates for the mean curves according to Fryer are close to those estimated for pooled data.

Individual haul and mean curves (Fryer and pooled data) are presented in Fig. 6. Some variability can be observed in the positions and shapes of the individual curves within the same cod end, which is expressed by D matrices (Table 3), suggesting that other variables besides mesh size have influenced the selectivity parameters.

4.3. Blue whiting

Blue whiting was captured in much greater numbers than hake, within a length class interval from approximately 14–30 cm (Fig. 7). The length frequency distributions were unimodal in all mesh sizes with the mode at 18 or 19 cm, except in the 65S, where a bimodal distribution was observed with the first mode at 17 cm and a minor peak at 20 cm. The numbers of

Table 2
Hake: summary of the hauls and catches for the different cod ends[a]

Haul no.	Date	Hour (start)	Depth (m)	Length range (cm)	Total catch (kg)	Cod end catch				Cover catch			
						Hake			Other (kg)	Hake			Other (kg)
						kg	No.	No. < MLS		kg	No.	No. < MLS	
65D, 63.5 mm													
19	8 August	13:05	342	13–47	481	12	175	171	292	6	143	143	172
24	9 August	13:45	356	11–64	324	29	254	226	123	4	113	113	168
26	10 August	6:20	276	08–53	307	19	149	119	239	4	126	126	45
27	10 August	8:15	305	07–47	287	22	127	86	211	3	94	94	51
28	10 August	10:10	358	11–53	438	23	259	237	131	6	186	186	278
$n = 5$				07–64	1837	105	964	839	995	23	662	662	715
$N_t = 13$				07–64	3740	140	1294	1113	2353	26	756	755	1222
$P = 0.38$					0.49	0.75	0.74	0.75	0.42	0.87	0.88	0.88	0.58
65S, 63.3 mm													
$N_t = 10$				11–59	3474	76	186	43	689	29.3	343	140	2680
70D, 69.4 mm													
8	06 August	11:10	350	14–64	309	9	48	40	190	3	68	68	107
14	07 August	14:10	348	12–54	349	13	136	129	228	8	174	174	101
31	11 August	6:30	274	10–46	257	10	106	94	181	5	119	119	62
33	11 August	10:20	353	10–64	509	22	116	90	161	8	217	217	318
35	11 August	14:15	310	10–71	236	11	63	47	132	3	137	137	90
$n = 5$				10–71	1661	65	469	400	893	26	715	715	678
$N_t = 18$				07–71	4673	128	970	775	2626	38	1078	1078	1880
$P = 0.28$					0.36	0.50	0.48	0.52	0.34	0.68	0.66	0.66	0.36
80D, 79.2 mm													
$N_t = 11$		$N_t = 19$		09–64	3787	167	1178	908	1654	35.3	1102	1102	1930

[a] N_t is the total number of hauls where the species was captured.

Table 3
Selectivity estimates for hake

Haul no.	L_{50}	95%CI for L_{50}	SR	95%CI for SR	SF	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}	Deviance	d.f.	*P*-value
65D													
19	18.8	18.1–19.4	5.3	3.2–7.3	3.0	−7.845	0.418	2.209	−0.1147	0.00600	7.69	15	0.94
24	17.5	16.9–18.1	4.0	2.8–5.2	2.8	−9.683	0.554	2.442	−0.1302	0.00699	7.74	32	1.00
26	18.6	17.9–19.3	5.5	3.6–7.4	2.9	−7.431	0.399	1.680	−0.0886	0.00473	19.78	32	0.96
27	18.2	17.5–19.1	5.0	3.1–6.8	2.9	−8.101	0.444	2.426	−0.1291	0.00696	7.63	33	1.00
28	17.5	17.0–18.0	4.8	3.5–6.1	2.7	−7.952	0.455	1.199	−0.0659	0.00365	9.56	25	1.00
MC Fryer	18.0	17.4–18.7	4.9	4.1–5.8	2.8	−7.999	0.444	0.413	−0.0236	0.00140			
MC pooled	17.0	16.7–17.3	5.2	4.5–5.9	2.7	−7.214	0.424	0.246	−0.0135	0.00075	26.50	46	0.99
D								0.244	−0.0210	0.00180			
65S													
MC pooled	25.0	23.7–26.2	5.6	4.3–6.9	3.9	−9.768	0.391	0.937	−0.0432	0.00205	20.69	34	0.96
70D													
08	21.0	20.1–20.9	3.9	1.9–6.0	3.0	−11.824	0.563	8.013	−0.3951	0.01960	3.77	17	1.00
14	20.5	20.1–21.0	3.7	2.5–4.8	3.0	−12.359	0.602	3.524	−0.1742	0.00866	5.65	18	1.00
31	19.6	19.0–20.2	4.0	2.5–5.5	2.8	−10.737	0.549	3.555	−0.1834	0.00953	4.82	23	1.00
33	20.3	19.6–20.9	3.9	2.6–5.2	2.9	−11.506	0.568	3.282	−0.1713	0.00900	13.15	29	0.99
35	19.3	18.4–20.1	4.2	2.7–5.6	2.8	−10.125	0.526	2.684	−0.1430	0.00775	13.97	24	0.95
MC Fryer	20.2	19.6–20.8	3.9	3.3–4.6	2.9	−11.103	0.551	0.854	−0.0409	0.00202			
MC pooled	19.2	19.0–19.4	3.9	3.5–4.4	2.4	−10.703	0.559	0.399	−0.0210	0.00111	13.43	43	1.00
D								0.611	−0.0178	0.00052			
80D													
MC pooled	18.8	18.6–19.0	4.4	3.9–4.9	3.0	−9.342	0.498	0.299	−0.0159	0.00086	11.32	42	1.00

individuals captured were similar in all cod ends, and the percentages of retention low, varying from 32 to 10% with increase in mesh size, while in the square mesh cod end less than 2% of the individuals entering the cod end were retained.

A summary of hauls and catches is presented in Table 4. A total of 10, 5 and 6 individual hauls were used for the estimation of between-haul variation in the 65, 70 and 80 mm mesh sizes, respectively, from a total of 13, 14 and 18 hauls. The reason for the small number of individual hauls in the 70 and 80D cod ends is related to the low retention of individuals of all sizes within the length range.

Blue whiting was the main catch in most of the hauls used for analysis with the exception of those carried out at depths lower than 300 m, where the boarfish and/or the horse mackerel accounted for the majority of the catches.

The selectivity estimates for the individual hauls and mean curves are given in Table 5. The large within-haul variability observed in some hauls is attributed to overdispersion, as seen by the high values obtained for the model deviance, exceeding those expected for binomially distributed data (Fryer, 1991). Overdispersion was already observed in similar data for blue whiting (Campos et al., 2003) and may indicate a failure of the assumption that the retention of each single fish entering the cod end is independent from other fish, due to schooling behaviour.

L_{50} estimates for the mean curves (Fryer and pooled data) coincide for the 65D cod end, while for the other cod ends some differences can be observed. An increase in L_{50} for the estimates according to Fryer from 22.7 to 24.1 cm when mesh size increased from 65 to 70D was observed, but a decrease to 22.5 cm was observed when the 80D cod end was used, similar to what happened with hake for the mean pooled curves. The correspondent L_{50} estimates for pooled data were 22.6, 25.1 and 25.4 cm. SR estimates slightly increase from 3.5 to 3.8 and 4.6 cm for the mean curves according to Fryer, while for the correspondent curves for pooled data slightly higher estimates between 5.1

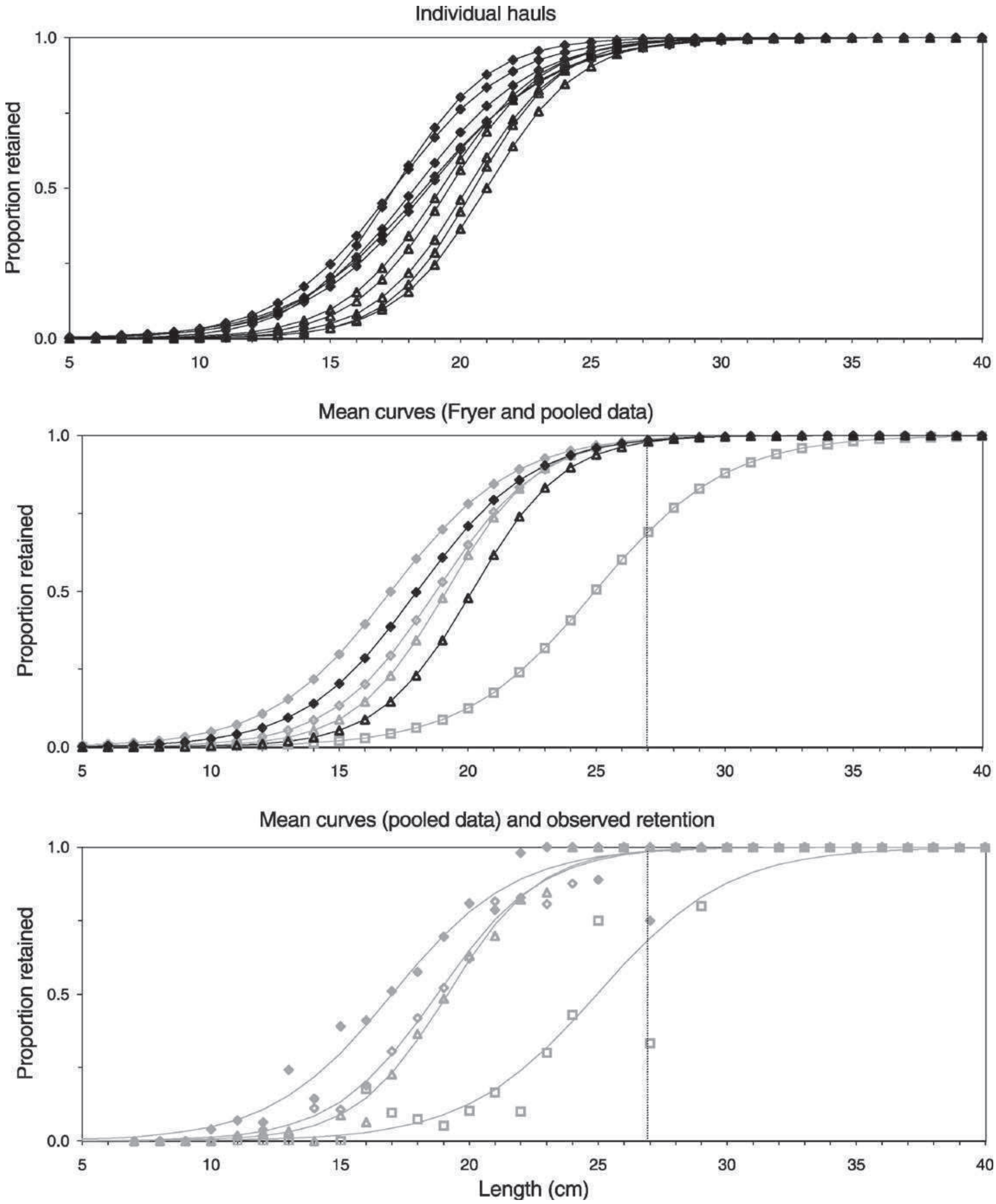

Fig. 6. European hake. Selectivity curves in the 65 and 70 mm mesh size cod ends for individual hauls and mean curves. Grey lines correspond to mean curves based on pooled data. 65D in black lozenges, 70D in triangles, 80D in white lozenges and 65S in squares. Vertical line MLS.

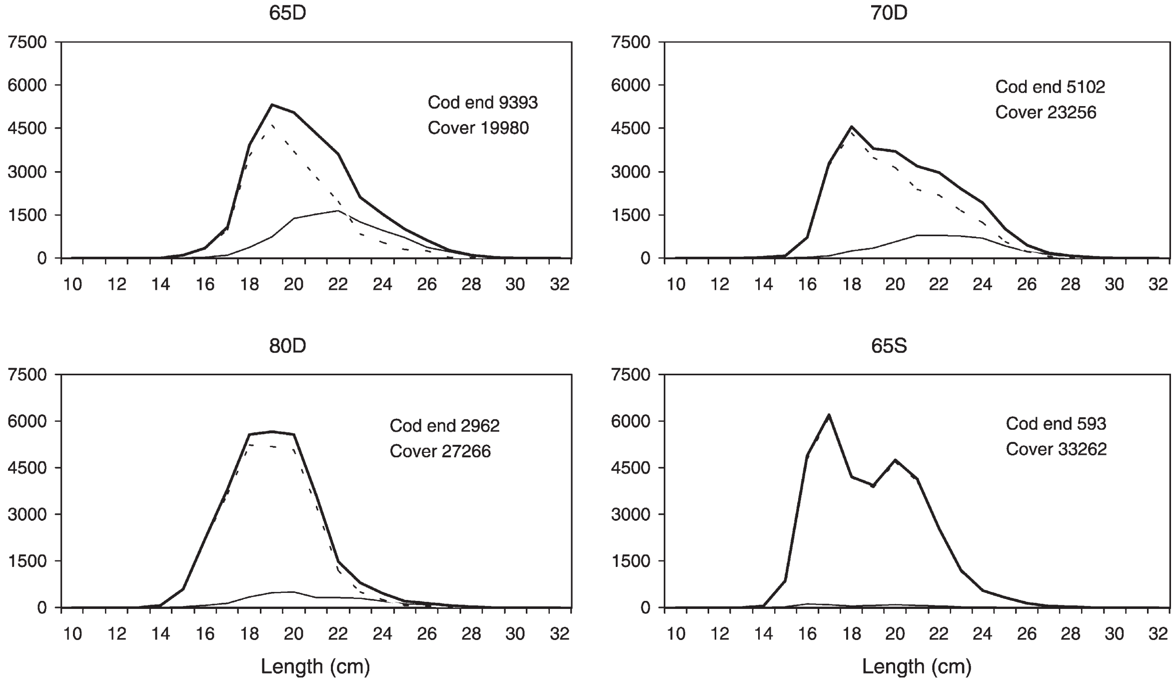

Fig. 7. Blue whiting. Size structure of the populations that entered the different cod ends. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers.

and 5.9 cm were obtained. In the square mesh cod end no selection curve could be estimated since virtually all the individuals have escaped.

Individual haul and mean curves (Fryer and pooled data) are presented in Fig. 8. The variability in position and shape of the individual curves within the same cod end, expressed by large values of the *D* matrices (Table 5) particularly for the 65 and 70D cod ends, suggests the influence of variables other than mesh size on the selectivity parameters estimated.

4.4. Horse mackerel

All horse mackerel were well above the minimum landing size of 15 cm. The length ranged from 22 to 32 cm in all mesh sizes (Fig. 9) showing unimodal distributions with the mode at 27 cm. Retention was around 100% in all diamond cod ends, while in the square mesh cod end a fraction of 40% of the total number of individuals entering this cod end escaped. Therefore, selectivity could be estimated only for this cod end, in which five individual hauls were used from a total of 10 where this species was caught (Table 6). Selectivity estimates for the 65S cod end are given in Table 7 while individual hauls and the mean curves are presented in Fig. 10.

4.5. Four-spot megrim

Four-spot megrim from 10 to 40 cm were caught in all cod ends (Fig. 11). Most of the fish were between 11 and 16 cm, with a distinct mode at 14 cm in all cod ends except the 80D (with the mode at 15 cm), and a small proportion of individuals between 17 and 40 cm. It can be observed (Fig. 12) that while the retention of smaller fish does not appear to be greatly influenced by changes in mesh size or in mesh configuration, a corresponding variation in selectivity is clear for the larger length classes, for which the change in mesh configuration from 65S to 65D or the increase in mesh size resulted in an increasingly greater opportunity of escaping. The square mesh cod end presents the lowest selectivity of all, even compared with the

Table 4
Blue whiting: summary of the hauls and catches for the different cod ends[a]

Haul no.	Date	Hour (start)	Depth (m)	Length range (cm)	Total catch (kg)	Cod end catch			Cover catch		
						Blue whiting		Other (kg)	Blue whiting		Other (kg)
						kg	No.		kg	No.	
65D, 63.5 mm											
16	8 August	6:30	362	15–27	250.9	105	1319	27	117	1822	2
19	8 August	13:05	342	16–30	481.3	116	1037	188	162	1821	16
20	8 August	15:20	352	16–28	199.7	12	162	152	32	600	3
21	9 August	6:25	365	15–27	197.6	51	810	94	40	738	13
22	9 August	8:40	355	15–26	140.7	52	801	40	42	780	6
23	9 August	11:00	369	14–28	267.4	27	447	157	50	898	33
24	9 August	13:45	356	15–27	323.9	75	1312	77	167	3870	5
26	10 August	6:20	276	15–29	307.3	8	77	250	8	111	42
27	10 August	8:15	305	13–30	286.7	13	186	220	16	355	38
28	10 August	10:10	358	15–31	437.9	48	781	106	276	6247	8
$n = 10$				13–31	2893	507	6932	1311	910	17242	166
$N_t = 13$				12–31	3740	704	9393	1788	1070	19980	178
$P = 0.77$					0.77	0.72	0.74	0.73	0.85	0.86	0.93
65S, 63.3 mm											
$N_t = 10$ ($N > 100$) individuals		$N_t = 10$		10–32	3474	28	593	737	1601	33262	1108
70D, 69.4 mm											
05	5 August	16:05	367	17–30	112.2	33	524	38	40	524	1
06	6 August	7:30	344	16–29	398.8	51	579	120	200	2325	28
07	6 August	9:20	343	17–29	235.1	42	445	82	101	1566	11
14	7 August	14:10	348	16–32	349.4	53	491	188	90	1037	19
15	7 August	16:25	370	18–29	139.1	33	450	56	44	519	6
$n = 5$				16–32	1235	212	2489	483	475	5971	65
$N_t = 14$				14–32	4673	497	5102	2257	1532	23258	387
$P = 0.36$					0.264	0.43	0.49	0.214	0.31	0.26	0.17
80D, 79.2 mm											
41	13 August	15:00	337	15–30	105	19	324	19	65	1278	3
42	13 August	16:50	359	14–28	32	13	256	9	7	166	2
46	14 August	12:15	306	14–27	124	8	89	87	7	139	21
47	14 August	14:35	303	16–29	78	9	122	42	15	240	12
66	18 August	14:30	286	11–30	81	4	52	59	6	131	11
67	18 August	16:10	290	13–28	146	9	99	113	9	188	14
$n = 6$				11–30	565	63	942	329	109	2142	64
$N_t = 18$				11–30	3787	178	2962	1644	1304	27266	662
$P = 0.33$					0.15	0.35	0.32	0.20	0.08	0.08	0.10

[a] N_t is the total number of hauls where the species was captured.

Table 5
Selectivity estimates for blue whiting

Haul no.	L_{50}	95%CI for L_{50}	SR	95%CI for SR	SF	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}	Deviance	d.f.	P-value	Sampling factor	
														Cod end, P_1	Cover, P_2
65D															
16	22.8	22.2–23.4	3.9	1.9–5.8	3.5	−12.989	0.570	7.3292	−0.3282	0.01474	19.46	7	0.01	0.190	0.239
19	25.9	25.2–26.6	4.4	2.7–6.0	4.0	−12.976	0.502	4.4373	−0.1781	0.00718	19.75	10	0.03	0.224	0.154
20	22.6	22.3–22.9	2.2	1.8–2.6	3.5	−22.520	0.996	3.0079	−0.1395	0.00650	14.01	11	0.23	1.000	1.000
21	20.8	20.6–21.1	3.0	2.2–3.8	3.2	−15.164	0.728	2.9578	−0.1416	0.00680	3.11	9	0.96	0.471	0.325
22	21.2	20.9–21.6	3.5	2.5–4.5	3.3	−13.353	0.629	2.9092	−0.1363	0.00641	3.36	9	0.95	0.327	0.405
23	21.7	21.3–22.1	3.4	2.6–4.2	3.3	−13.996	0.645	1.8261	−0.0889	0.00434	6.33	11	0.85	1.000	0.300
24	21.7	20.8–22.7	3.3	1.9–4.8	3.3	−14.324	0.659	6.8633	−0.3422	0.01713	46.77	11	0.00	0.267	0.267
26	23.6	23.0–24.3	3.7	2.4–5.0	3.6	−14.114	0.598	5.0202	−0.2147	0.00924	14.21	13	0.36	1.000	1.000
27	22.5	21.5–23.5	5.8	4.0–7.6	3.5	−8.532	0.379	1.317	−0.0616	0.00294	33.62	15	0.00	1.000	1.000
28	24.0	22.9–25.0	4.5	3.4–5.7	3.7	−11.568	0.483	1.1879	−0.0598	0.00303	8.86	13	0.78	0.292	0.109
MC Fryer	22.7	21.7–23.5	3.5	3.0–4.4	3.5	−13.644	0.605	1.439	−0.0665	0.00321					
MC pooled	22.6	22.3–23.0	5.1	4.4–5.8	3.5	−9.743	0.430	0.350	−0.0164	0.00078	319.78	18	0.00		
D								11.074	−0.5131	0.02506					
70D															
05	21.3	21.0–21.7	4.7	3.0–6.4	3.3	−10.032	0.470	2.530	−0.1189	0.00560	10.25	8	0.25	1.000	0.500
06	27.0	25.9–28.1	5.4	3.8–7.0	4.2	−10.964	0.406	1.568	−0.0655	0.00275	9.87	9	0.36	0.333	0.200
07	24.8	23.9–25.6	3.5	2.2–4.7	3.8	−15.653	0.632	5.577	−0.2413	0.01049	25.98	11	0.01	0.333	0.307
14	25.4	25.0–25.9	2.9	2.2–3.7	3.9	−18.995	0.747	5.190	−0.2108	0.00858	1.85	12	1.00	0.377	0.222
15	22.5	22.0–23.8	3.6	2.3–4.9	3.5	−13.933	0.618	4.535	−0.2042	0.00923	2.60	7	0.92	0.333	0.318
MC Fryer	24.1	22.4–26.1	3.8	2.9–5.5	3.7	−13.415	0.553	2.754	−0.1025	0.00421					
MC pooled	25.1	24.4–25.8	5.9	5.0–6.9	3.9	−9.295	0.370	0.345	−0.0158	0.00073	255.32	16	0.00		
D								10.137	−0.3549	0.01417					
80D															
41	23.7	22.7–24.8	5.7	4.1–7.3	3.7	−9.192	0.387	1.030	−0.0509	0.00253	18.05	13	0.16	1.000	0.308
42	18.9	18.3–19.5	4.7	3.2–6.2	2.9	−8.848	0.468	1.787	−0.0899	0.00455	7.83	10	0.65	1.000	1.000
46	22.9	22.1–23.7	4.4	3.1–5.8	3.5	−11.387	0.497	2.366	−0.1047	0.00468	15.61	12	0.21	1.000	1.000
47	24.7	21.7–27.8	9.5	2.2–16.8	3.8	−5.720	0.231	3.301	−0.1471	0.00666	48.39	12	0.00	1.000	1.000
66	23.6	22.7–24.5	4.1	2.5–5.6	3.6	−12.738	0.541	4.506	−0.1987	0.00884	3.75	11	0.98	1.000	1.000
67	23.6	22.7–24.4	4.1	2.7–5.6	3.6	−12.590	0.534	4.137	−0.1783	0.00776	24.33	14	0.04	1.000	1.000
MC Fryer	22.5	21.3–24.4	4.6	4.4–6.5	3.5	−9.825	0.432	0.949	−0.0382	0.00177					
MC pooled	25.4	24.3–26.4	5.5	4.5–6.6	3.9	−10.082	0.397	0.539	−0.0262	0.00129	252.62	17	0.00		
D								3.119	−0.1128	0.00529					

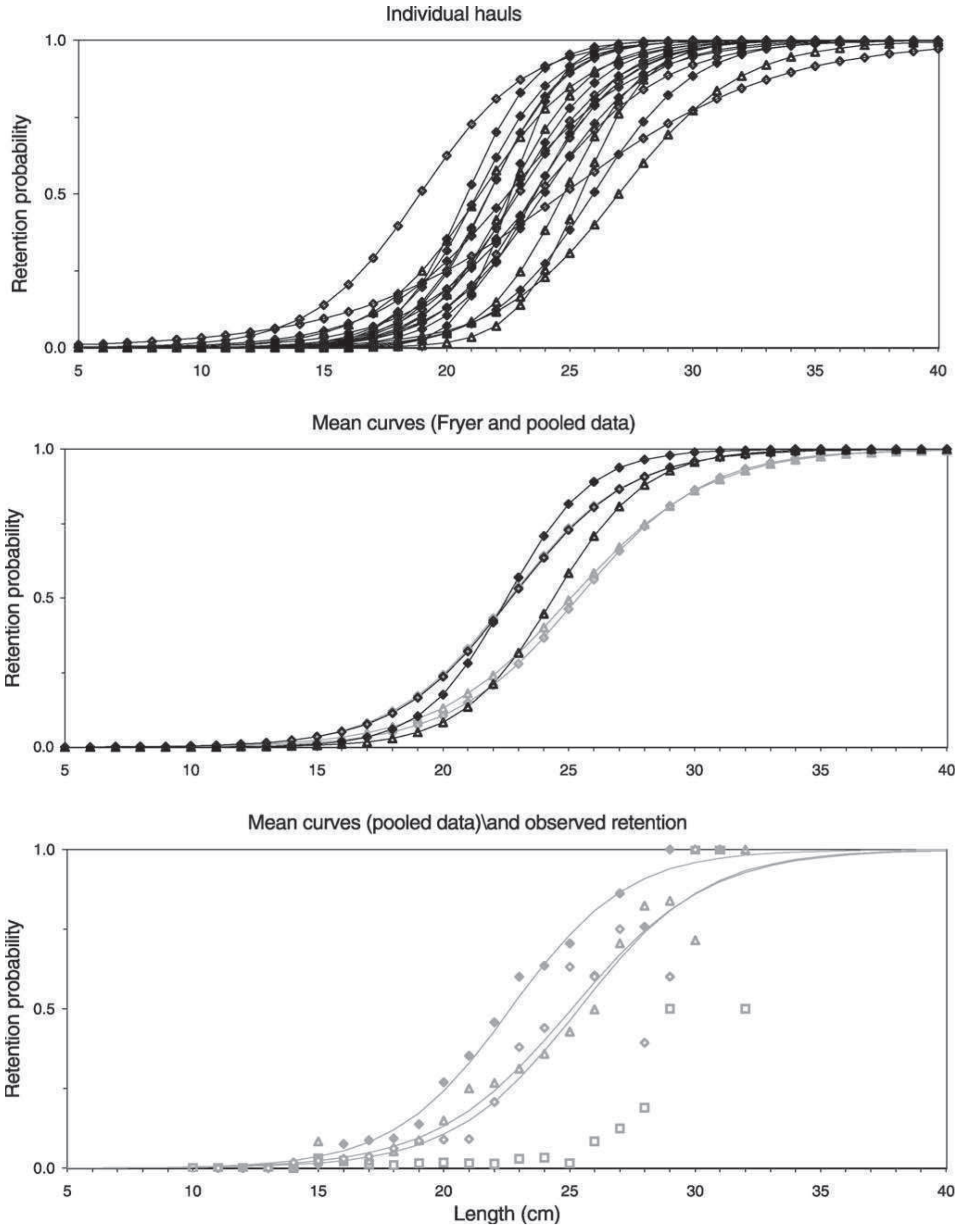

Fig. 8. Blue whiting. Selectivity curves in the diamond cod ends for individual hauls and mean curves. Grey lines correspond to mean curves based on pooled data. 65D in black lozenges, 70D in triangles, 80D in white lozenges and 65S in squares.

65D, retaining all the fish larger than 17 cm, as can be seen in Fig. 12 and confirmed by the selectivity parameters in Table 8. A small increase in L_{50} from 16.7 to 17.5 cm can be noticed with the corresponding increase in mesh size from 65 to 70 diamond mesh, while a more pronounced increase to 21.0 cm is observed when the 80D cod end was used. On the other hand, the L_{50} estimate in the 65 mm square mesh cod

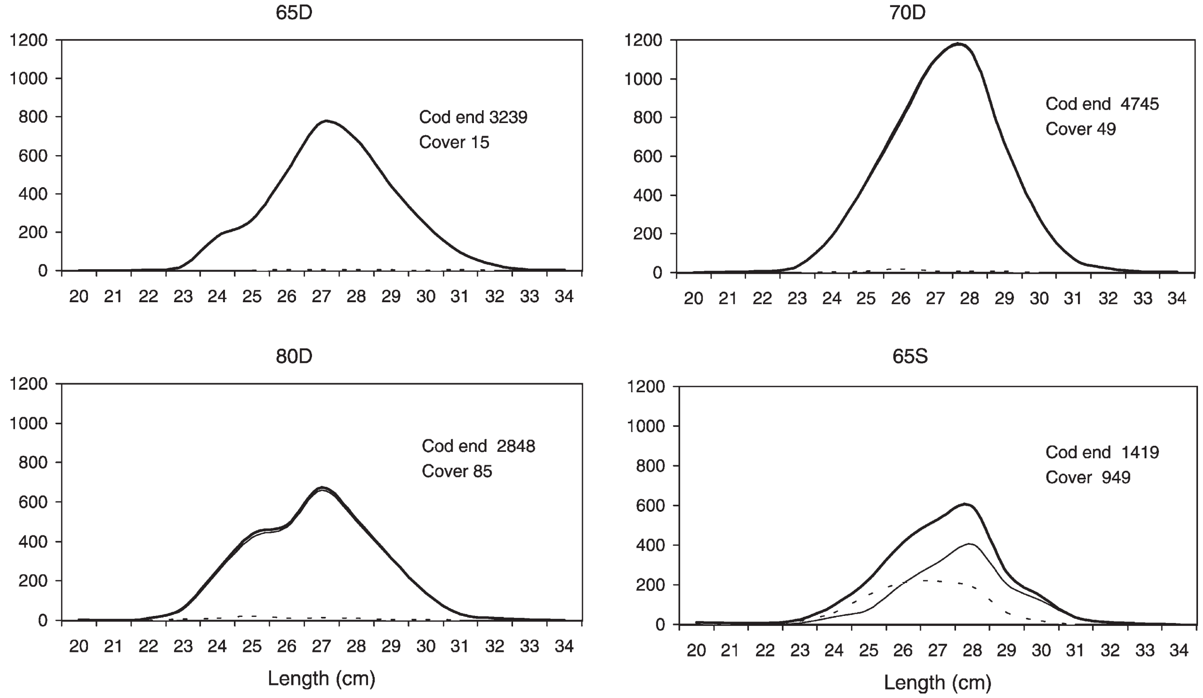

Fig. 9. Horse mackerel. Size structure of the populations that entered the different cod ends. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers.

end was the lowest (16.0 cm). SR estimates follow the same trend with the lowest SR in the square mesh cod end (2.8 cm) and increasing up to 6.5 cm in the 80D cod end.

Fryer's (1991) model was employed to investigate the between-haul variation of L_{50} and SR for hake and blue whiting, and their dependence on the explanatory variables mesh size, m_i and cod end catch, c_i, while for horse mackerel only the last variable was considered. Three models are presented which were found to best describe the data

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_3 m_i + \alpha_5 c_i \\ \alpha_2 + \alpha_4 m_i \end{pmatrix}$$

for the European hake,

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_1 + \alpha_2 m_i + \alpha_4 c_i \\ \alpha_3 m_i \end{pmatrix}$$

for blue whiting,

and

$$E\begin{pmatrix} L_{50} \\ \mathrm{SR} \end{pmatrix} = \begin{pmatrix} \alpha_1 \\ \alpha_2 c_i \end{pmatrix} \quad \text{for horse mackerel.}$$

The alpha estimates are given in Table 9 along with their respective standard errors and t-values. The latter give an idea of the relative importance of the different variables in the models. Positive effects of mesh size and cod end catch on L_{50} were found for hake and blue whiting, while SR for blue whiting was found to be positively affected only by the mesh size, and for hake negative effects on SR of this variable were estimated. For horse mackerel, positive effects of the cod end catch on SR were estimated in the selectivity model proposed for the 65S cod end. According to the proposed models, an increase of 10 mm in mesh size while maintaining a constant cod end catch leads to correspondent expected increases of 3.8 and 1.4 cm in L_{50} for hake and blue whiting, respectively. On the other hand, the correspondent effects of an increase of 100 kg in cod end catch are of 1.1 and 2.1 cm, within

Table 6
Horse mackerel: summary of the hauls and catches for the different cod ends[a]

Haul no.	Date	Hour (start)	Average depth (m)	Length range (cm)	Total catch (kg)	Cod end catch				Cover catch			
						Horse mackerel			Other (kg)	Horse mackerel			Other (kg)
						kg	No.	No. < MLS		kg	No.	No. < MLS	
65D, 63.5 mm													
$N_t = 13$				22–37	3740	534	3239	0	1958	3	15	0	1245
65S, 63.3 mm													
49	15 August	9:05	304	20–32	142	35	195	0	29	14	96	0	65
52	15 August	15:45	235	12–33	745	9	49	0	107	6	54	4	623
54	16 August	8:40	368	23–31	352	28	146	0	66	67	347	0	191
56	16 August	12:40	348	20–33	557	40	245	0	79	22	134	0	416
57	16 August	14:35	352	23–32	425	32	166	0	36	37	232	0	320
$n = 5$				12–33	2221	144	801	0	316	146	863	0	1615
$N_t = 10$				12–34	3474	252	1419	0	512	175	949	4	2534
$P = 0.50$					0.64	0.57	0.56		0.62	0.83	0.91		0.64
70D, 69.4 mm													
$N_t = 18$				17–36	4673	814	4745	0	1941	8	49	0	1910
80D, 79.2 mm													
$N_t = 19$				19–33	3787	406	2848	0	1415	12	85	0	1954

[a] N_t is the total number of hauls where the species was captured.

Table 7
Selectivity estimates for horse mackerel in the 65 mm square mesh cod end

Haul no.	L_{50}	95%CI for L_{50}	SR	95%CI for SR	SF	v_{i1}	v_{i2}	R_{i11}	R_{i12}	R_{i22}	Deviance	d.f.	P-value
65S													
49	26.4	26.0–26.8	2.5	1.8–3.2	4.2	−23.312	0.883	8.790	−0.3249	0.0120	6.8	10	0.74
52	26.1	25.1–27.1	4.0	2.3–5.8	4.1	−14.243	0.545	8.270	−0.3138	0.0120	5.3	15	0.99
54	29.5	28.6–30.4	4.0	2.1–5.8	4.7	−16.317	0.553	8.721	−0.3119	0.0112	7.5	7	0.38
56	26.6	26.1–27.1	3.4	2.3–4.4	4.2	−17.275	0.650	6.065	−0.2210	0.0081	3.8	10	0.96
57	28.3	27.9–28.7	3.2	2.3–4.2	4.5	−19.229	0.680	5.544	−0.1987	0.0071	2.3	8	0.97
MC Fryer	27.3	26.1–28.6	3.4	2.8–3.9	4.3	−17.944	0.658	2.051	−0.0786	0.00322			
MC pooled	26.1	25.8–26.3	5.3	4.5–6.1	4.1	−10.851	0.416	0.603	−0.0223	0.00083	22.2	13	0.05
D								3.000	−0.1273	0.00636			

Table 8
Selectivity parameter estimates for the four-spot megrim

Selectivity estimates	65D (13 hauls)	70D (18 hauls)	80D (18 hauls)	65S (10 hauls)
Retained				
<MLS	60	109	69	102
≥MLS	66	165	64	133
Escapees				
<MLS	214	498	559	277
≥MLS	0	7	34	4
v_1	−10.581	−8.458	−7.115	−12.709
v_2	0.635	0.484	0.340	0.796
R_{11}	1.359	0.683	0.485	1.574
R_{12}	−0.0879	−0.0422	−0.0277	−0.1049
R_{22}	0.00579	0.00268	0.00166	0.00707
L_{50} (cm)	16.7	17.5	21.0	16.0
L_{25} (cm)	14.9	15.2	17.7	14.6
L_{75} (cm)	18.4	19.8	24.2	17.3
CI L_{50} (cm)	16.0–17.3	16.8–18.2	19.6–22.3	15.5–16.4
SR (cm)	3.5	4.5	6.5	2.8
CI SR (cm)	2.6–4.3	3.5–5.6	4.9–8.1	2.1–3.4
SF	2.6	2.5	2.6	2.5
Deviance	14.8	49.1	37.6	13.6
d.f.	18	24	22	18
P-value	0.68	0.00	0.02	0.75

the same mesh size. For horse mackerel, a similar increase of cod end catch leads to an increase in SR of approximately 3.7 cm.

5. Discussion

Hake and blue whiting were captured in a number of hauls in quantities and length class ranges that allowed for the fitting of individual curves and the estimation of significant positive effects of cod end catch on L_{50}, in addition to the effects of mesh size. However, this was only possible within the diamond mesh cod ends. The degree of escapement of both species from the square mesh cod end was so great that the estimation of selectivity parameters for hake could only be carried out based on pooled data, while for blue whiting even a pooled selection curve could not be fitted.

The opposite was observed for the horse mackerel, where only large sized individuals between 22

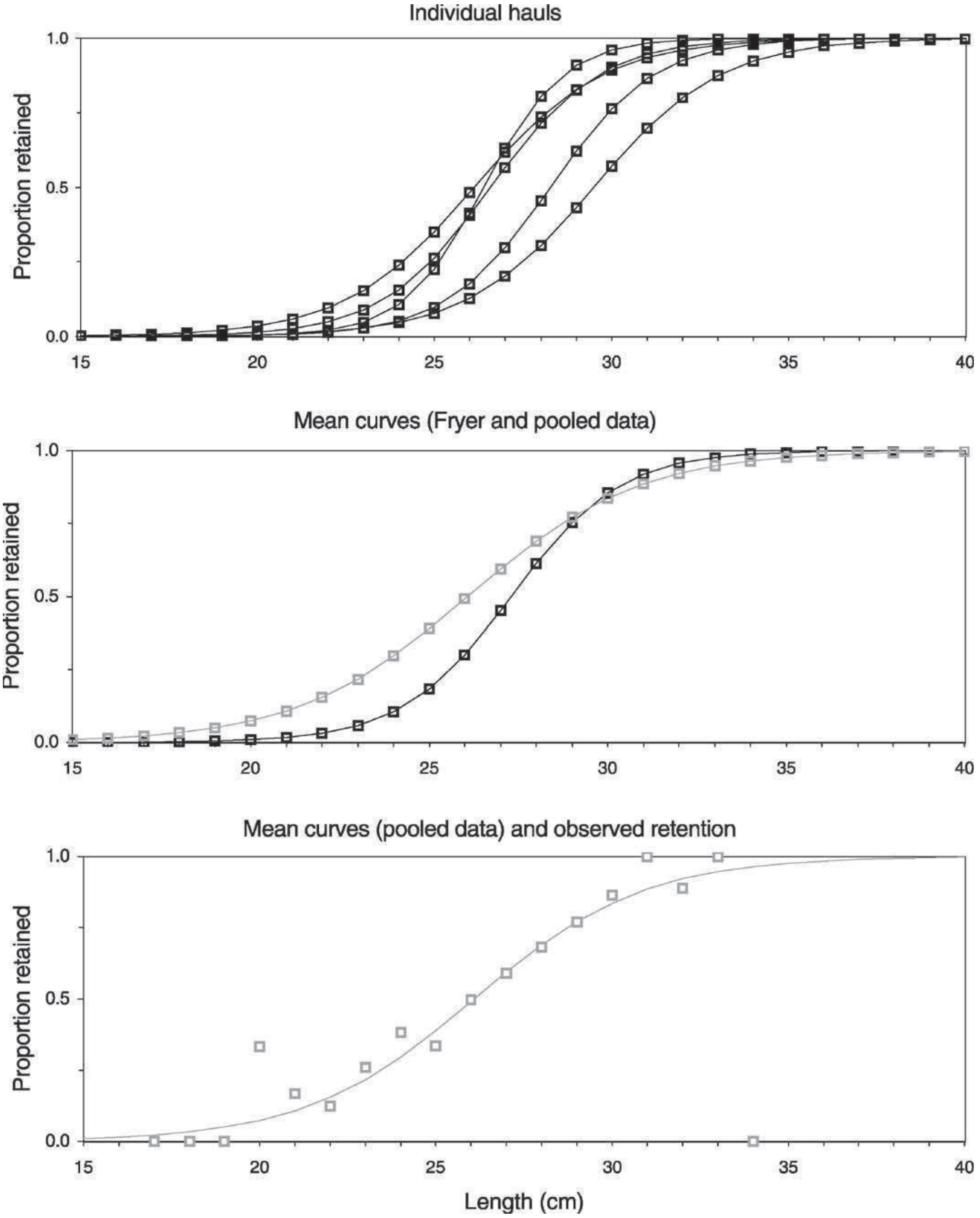

Fig. 10. Horse mackerel. Selectivity curves in the 65 mm square mesh cod end for individual hauls and mean curves. Grey lines correspond to mean curves based on pooled data. Vertical line MLS.

and 32 cm were captured. The retention was close to 100% in all the diamond mesh cod ends and therefore the selectivity could only be estimated for the square mesh cod end, for which a mean curve was fitted taking into account the between-haul variation of five hauls.

Due to the particular data structure, the effects of changing mesh configuration could not be evaluated

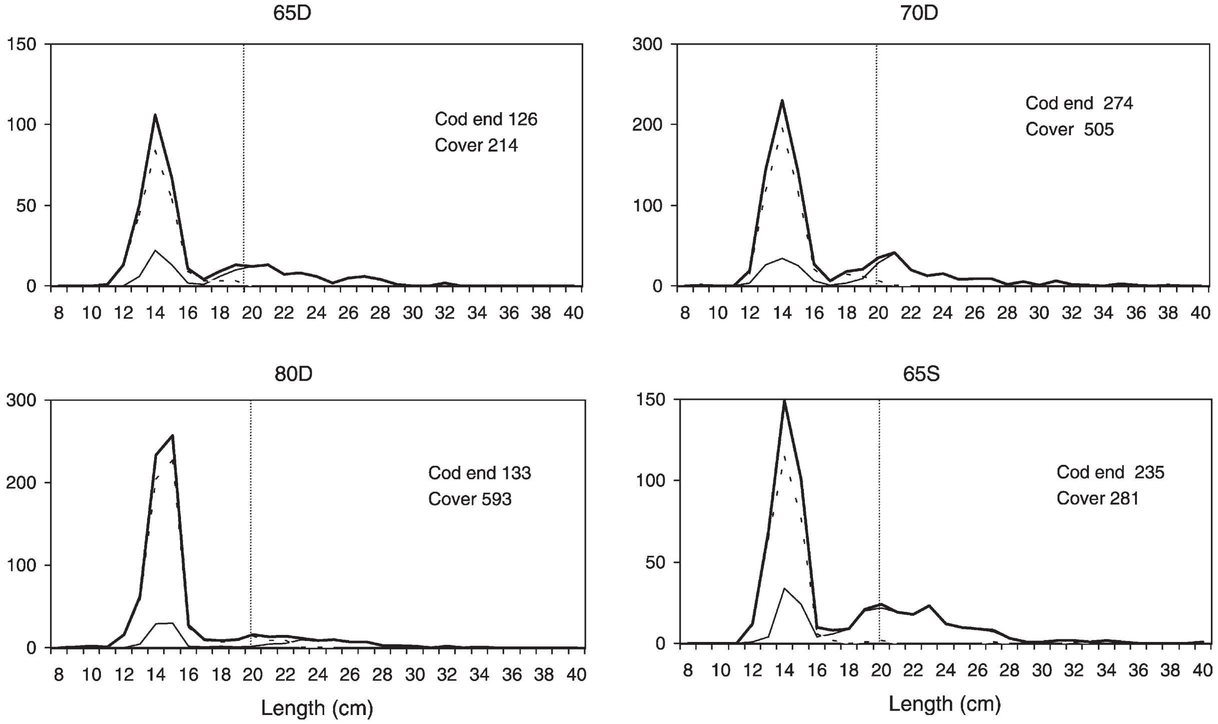

Fig. 11. Four-spot megrim. Size structure of the populations that entered the different cod ends. Thin line corresponds to length frequency in cod end, dashed line in cover and thick line to total numbers. Vertical line MLS.

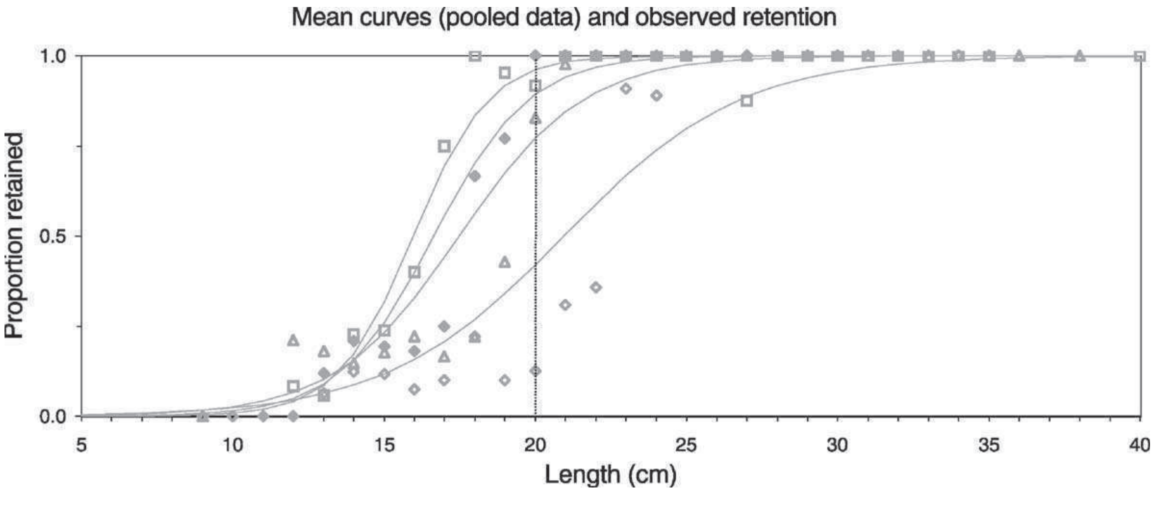

Fig. 12. Four-spot megrim. Selectivity based on pooled data: 65D in black lozenges, 70D in triangles, 80D in white lozenges and 65S in squares. Vertical line MLS.

Table 9
Parameter estimates for the species in study along with the respective standard errors and *t*-values

Parameters	Estimate	Standard error	*t*-Value
European hake			
α 1 (constant)	−8.394	2.98	−2.8
α 2 (constant)	13.244	3.53	3.8
α (mesh size)	0.381	4.37×10^{-2}	8.7
α (mesh size)	−0.136	5.28×10^{-2}	−2.6
α 5 (cod end catch)	0.011	2.22×10^{-3}	4.9
Blue whiting			
α 1 (constant)	10.326	4.54	2.3
α 2 (mesh size)	0.141	5.83×10^{-2}	2.4
α 3 (mesh size)	0.055	2.72×10^{-3}	20.4
α 4 (cod end catch)	0.021	5.28×10^{-3}	4.0
Horse mackerel			
α 1 (constant)	27.034	5.36×10^{-1}	50.4
α 2 (cod end catch)	0.037	4.72×10^{-3}	7.8

in the selectivity models proposed. However, the alteration in mesh configuration had an important impact on the selectivity for hake and blue whiting, as it can be seen in Tables 3 and 5 and Figs. 6 and 8, and particularly for horse mackerel, if the catches in the different cod ends (Table 6) and the respective length frequency distributions (Fig. 9) are considered.

For the four-spot megrim the data structure did not allow for a haul-by-haul analysis, but selectivity curves could be estimated for all the cod ends based on pooled data. A highly significant increase in selectivity could be detected with the corresponding increase in mesh size, as shown by the results of the likelihood ratio test comparing successive pairs of mesh sizes. However, no significant differences were found when the 65D and the 65S cod ends were compared ($P = 0.141$, Table 10), indicating that the four-spot megrim did not profit from the increase in the escape area provided by the change from diamond to square mesh. This is due to the laterally compressed body shape for this species whose escapement is favoured in diamond mesh configuration cod ends. Similar results have been obtained for this species by Petrakis and Stergiou (1997) in the Mediterranean, and by other authors for different flatfish species such as the winter flounder *Pseudopleuronectes americanus* (Simpson, 1989), the American plaice *Hippoglossoides platessoides* (Walsh et al., 1992) and the sole (Fonteyne and M'Rabet, 1992).

Table 10
Four-spot megrim: results (*P*-values) of the likelihood ratio test pairs of selection curves

	P-value
65S/65D	0.141
65D/70D	<0.001
70D/80D	<0.001

Cod end catch was found to positively affect hake and blue whiting L_{50}, while for horse mackerel positive effects of cod end catch on SR were found. The importance of this variable on L_{50} is lower for hake when compared to mesh size, while for blue whiting it is slightly higher, as shown by the *t*-values in Table 9. Similar effects of cod end catch on L_{50} had already been found by O'Neill and Kynoch (1996) for haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*), and also by Campos et al. (2003), for blue whiting captured as a by-catch in the Portuguese crustacean fishery. On the other hand, Suuronen et al. (1991), Madsen and Moth-Poulsen (1994) and Madsen et al. (1998) reported negative effects of this variable on L_{50}, for herring (*Clupea harengus*), whiting and Baltic Sea cod (*Gadus morhua*), respectively. Of all these studies, only the last two reported a clear variation in SR with the increase in cod end catch, but while in Madsen and Moth-Poulsen (1994) a reduction in SR is reported, in Madsen et al. (1998) a positive effect of catch on SR was found.

However, the range of catches analysed by the different authors varied considerably. While O'Neill and Kynoch (1996) and Campos et al. (2003) analysed relatively small catches from 100 to 400 and 30 to 300 kg, respectively, in the other experiments the catches were much greater. O'Neill and Kynoch (1996) suggest an initial increase in selectivity as the catch builds up and the meshes in front of the cod end open wider, up to a point where the maximum mesh opening is achieved and any further increase in catch size tends to reduce selectivity due to mesh clogging.

The effects of cod end catch in this study were estimated based on a narrow range of small catches of approximately 60–300 kg, similar to those reported by Campos et al. (2003). Furthermore, these effects were not addressed but incidentally observed, as in all the above mentioned studies except that by O'Neill and

Kynoch (1996), and they deserve further attention. It is expected that they may become more evident if a wider catch range is under analysis, which is closely dependent on haul duration. It must be noted that haul duration in this work was one hour only, and this explains the low catches for most of the hauls.

Comparison of the present results with those obtained for hake and horse mackerel captured on the continental shelf at depths from 50 to 100 m off the southwest coast (Campos and Fonseca, 2003), show that for hake higher SF estimates were found herein for the diamond mesh cod ends. For horse mackerel a higher SF was found in the square mesh cod end, while for hake the opposite was observed.

It is always difficult to explain differences in selectivity between experiments since the experimental conditions can change from one experiment to another. However, the same gear and experimental method were used in both experiments and therefore the fishing depth, which is associated with differences in the abundance and length composition, is probably the major source for the differences found in selectivity for horse mackerel and hake. While juveniles of horse mackerel are mainly concentrated on the continental shelf (Murta and Borges, 1994), the adults can be also found on the shelf until the winter–spring spawning, after which they apparently move to the deeper waters of the upper slope, where they are captured in the summer (Borges and Gordo, 1991; Murta and Borges, 1994). Therefore, in Campos and Fonseca (2003) the estimation of selectivity was based on length classes from 12 to 25 cm approximately, while in the present study the captures ranged from 23 to 32 cm. This explains the total retention observed herein for the diamond mesh cod ends, while in the square mesh cod end higher retention was also observed when compared to previous data, but the selectivity estimates are higher due to the completely different data structure.

For hake, the concentration of the lower length classes, including recruits under 17 cm which escaped in high proportions from all cod ends was much higher in the present experiment when compared to the previous data from 50 to 100 m, which is in accordance with Cardador (1995) for the length distribution of this species according to depth, and therefore the selectivity was estimated from different size distributions as well.

6. Conclusions

Morphological differences, as well as differences in size range between the four species studied, resulted in differences in cod end selectivity which support the idea that mesh size or mesh configuration regulations may be of limited use when managing multi-species fisheries. In fact, while for hake these data suggest that the adoption of square mesh cod ends of 65 mm mesh size would be an option to bring the L_{50} to a value near the MLS of 27 cm, for horse mackerel the use of the 65S cod end resulted in a significant loss of fish above the respective MLS of 15 cm. Conversely, for the four-spot megrim, no significant differences were found between selectivity in the 65D and 65S cod ends, where high proportions of fish below the MLS of 18 cm were retained, suggesting that an increase in mesh size would be advisable.

Selectivity models are proposed for the first time in this study for hake and horse mackerel. However, the proposed models should be carefully considered for a number of reasons. Firstly, they are based on a low number of individual hauls, particularly for horse mackerel and hake, for which only five individual hauls could be considered in each of the cod ends in study. For blue whiting a higher number of individual hauls was analysed in the 65 mm cod end (10 hauls), but only five and six hauls could be considered in the 70 and 80D cod ends respectively. Furthermore, this experiment was primarily designed to estimate the effects of increasing cod end mesh size on selectivity, and, to a lesser extent, the effects of changing mesh configuration, since only a 65 mm square mesh cod end was tested. The effects of cod end catch were not addressed but incidentally observed. However, these effects were consistently estimated for a number of fish species in several studies, including a previous study by the same authors, for blue whiting off the Portuguese south coast (Campos et al., 2003), and therefore deserve further attention in future selectivity studies.

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Evaluation of separator panels and square mesh windows as by-catch reduction devices in the Algarve (South Portugal) crustacean trawl fishery

Aida Campos, Paulo Fonseca

IPIMAR, Portuguese Institute for Fisheries and Sea Research, Avenida de Brasília, 1449-006, Lisbon, Portugal

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Abstract

The effectiveness of oblique separator panels used in association with square mesh windows in reducing by-catch consisting mainly of the boarfish (*Capros aper*) and the blue whiting (*Micromesistius poutassou*) is evaluated in the Algarve crustacean trawl fishery.

The results obtained from three different panel/window mesh size combinations and the window alone, suggest that the amount of blue whiting excluded from the trawl was independent of the use of the separator panel, as well as of the range of mesh sizes used in the panel and in the square mesh window, varying between 67 and 71% of the total species catch. On the other hand, the window mesh size proved to significantly affect the escape of boarfish, with the average escape percentage rising from about 10 to a maximum of 44% when mesh size increased from 70 to 100 mm. The best results, in terms of the maximization of by-catch exclusion while limiting the losses of the target species, were obtained with the simultaneous use of a 120 mm separator panel and the 100 mm square mesh window. For this combination, losses of commercial sized rose shrimp *Parapenaeus longirostris*, the main target species, were low (4.3%), while 42% of the boarfish escaped. In hauls where the square mesh window was used alone, only blue whiting presented a significant escape behaviour, with an average of 67% of escapees, while boarfish escaped in much lower proportions and loss of shrimp above the minimum landing size was observed. In spite of the efficiency of the sorting devices as by-catch excluders, the technical difficulties involved in the construction, mounting and use of the flexible separator panels are found to be major drawbacks to their commercial use. Further assessment of square mesh windows placed in the cod end or of sorting grids associated with fish escape holes is recommended.

Keywords: By-catch reducing devices; Separator panel; Square mesh window; *Parapenaeus longirostris*; *Nephrops norvegicus*; *Capros aper*; *Micromesistius poutassou*; *Trachurus trachurus*; Portuguese continental waters

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1. Introduction

As in many crustacean trawl fisheries worldwide, the amount of by-catch in the crustacean trawl fishery off the coast of Algarve can largely exceed the catch of the target species, the rose shrimp, *Parapenaeus longirostris*, the Norway lobster, *Nephrops norvegicus*, and the red shrimp, *Aristeus antennatus*. While some of the by-catch is landed, contributing to a significant proportion of the total income of this fishery, a large amount of fish, crustaceans and cephalopods is discarded at sea. According to Borges et al. (2001), an average of 70% of the total catch in weight per trip was discarded in this fishery during

1995-96, while a drop to 43% was observed in 1997-99 (Borges et al., unpublished data). These latter report blue whiting, *Micromesistius poutassou*, as the most discarded species in recent years, accounting for 25% of the total weight of discards.

The improvement of the selectivity of crustacean trawls by increasing the current cod end mesh size or changing mesh shape was previously addressed (Campos et al., 2002; Campos et al., 2003), in experiments where the blue whiting and the boarfish (*Capros aper*) accounted for 48 and 15%, respectively, of the total catch. The results obtained suggested that an increase in cod end mesh size from 55 to 70 mm diamond mesh would contribute to the decrease in the retention of undersized shrimp, while allowing for the escape of approximately 63% in weight of the blue whiting and 50% of the boarfish.

Despite the good results obtained, it was thought that further improvements in the exclusion of non-commercial by-catch could be achieved, while maintaining commercial catches of crustaceans, by using sorting mechanisms based on a higher degree of active escape behaviour, as is the case for separator panels associated with square mesh windows, instead of mesh size sorting in the cod end. The use of these types of devices has the further advantage of improving fish quality for the marketable species, by facilitating the escape of by-catch species before they reach the cod end, thus reducing the compression to which the catch is submitted.

Separator panels of different types have been tested in crustacean fisheries: horizontal panels, with the aim of separating benthic species such as the Norway lobster and flatfish from higher swimming fish such as haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus* into two cod ends of different mesh sizes (Main and Sangster, 1982a,b; 1985a,b); and oblique panels, mounted in the rear part of the trawl in association with escape openings. The latter were tested to exclude fish species such as Norway pout, *Trisopterus esmarki*, cod, *Gadus morhua*, haddock, and European flounder, *Platichthys flesus*, from trawls targeting the pink shrimp, *Pandalus borealis* (Karlsen, 1976, 1988; Karlsen and Mathai, 1978), and they were commercially introduced in Norway in 1985. A different concept of oblique panel separating the trawl into two sections was developed by Sørensen and Yngvesson (1987) for the Danish fishery for pink shrimp in the northwestern North Sea, where by-catch includes a large fraction of round fish including Norway pout, cod and haddock, and also benthic species such as the Norway lobster, monkfish and several flatfish species, similarly to what happens in the Portuguese fishery.

Square mesh windows of different mesh sizes placed in the cod end or in the trawl upper belly, before the cod end, have also been tested in recent years, as by-catch excluders in Norway lobster fisheries. Hillis et al. (1991), Thorsteinsson (1991), Robertson and Shanks (1994), and Armstrong et al. (1998) point out the effectiveness of these devices installed in the upper bellies, in excluding whiting, with acceptable losses of *Nephrops* above the minimum landing size. On the other hand, Briggs and Robertson (1993), in studies on fish behaviour using a remote controlled towed vehicle, reported active escape behaviour for whiting and horse mackerel through diamond and square mesh escape panels placed in the cod end extension.

The present paper analyses the effectiveness of using an oblique separator panel similar to that developed by Sørensen and Yngvesson (1987), to separate crustaceans and benthic fish species from other fish in two different cod ends, in association with a square mesh window placed in the upper trawl belly, above the separator panel, for the purpose of excluding the non-commercial fish by-catch guided by the panel into the trawl upper level.

2. Materials and methods

2.1. Sorting devices

The sorting devices initially tested (Fig. 1) included an oblique separator panel installed in the rear part of the trawl, starting 11 metres before the cod end joining row, designed to separate the crustacean and benthic fish species from the remaining by-catch in two different cod ends, and a square mesh window placed in the trawl upper belly, above the separator panel, to allow for the escapement of those species with greater swimming ability. Prior to field experiments 1:4 model tests of the trawl equipped with the sorting devices were carried out in the flume tank of

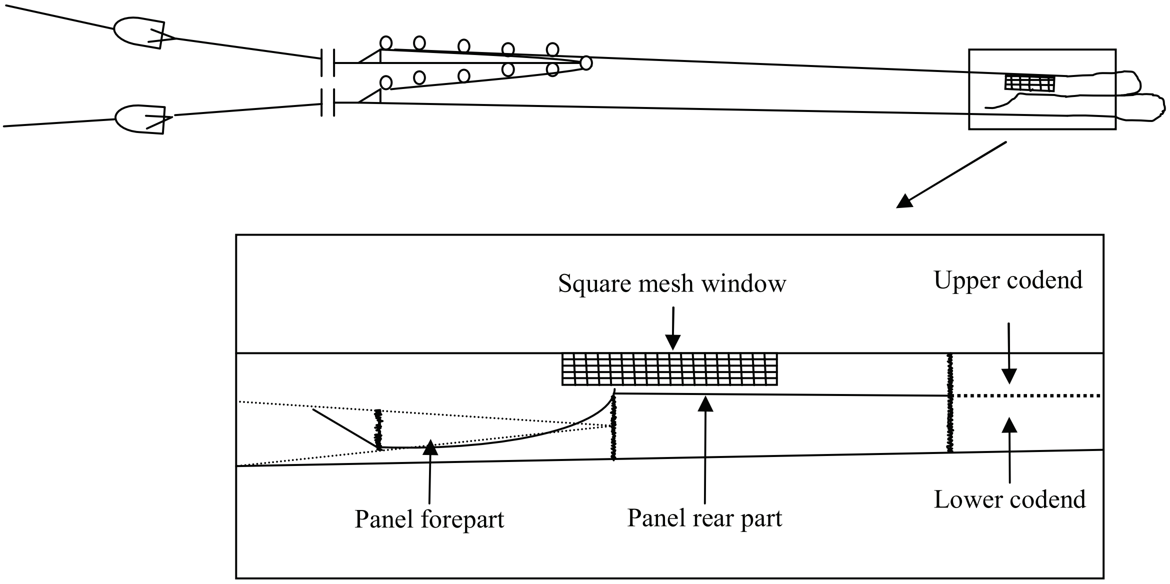

Fig. 1. Side view of the trawl with sorting panel and square mesh

the former Danish Institute of Fishing Technology and Aquaculture (Campos et al., 1996).

The separator panel design included an upward sloping forepart made in big meshes (120 mm mesh size), made of white twisted polyamide 1.8 mm twine thickness, weighted with a leadline, installed with the purpose of guiding the higher swimming fish to the upper trawl section. It was followed by an horizontal small mesh rear part in braided polyethylene 55 mm and 1.8 mm twine thickness, separating the trawl section into two different compartments ending in a lower and an upper cod end. The sides of the panel forepart were laced to the trawl upper panel along a line of bars. Between the two parts a constrictor rope was mounted in order to control the steepness of the forepart slope.

The large mesh forepart was designed to allow shrimp species to pass through and be retained by the lower cod end, while the opening between the lower belly and the panel allows for the passage of the Norway lobster and the benthic fish species directly into the lower cod end. This specific design maximizes the vertical area covered by the panel, thus allowing a reduction of the direct openings to the cod ends. A high proportion of all fish and shrimp entering the trawl was expected to get into contact with the panel, irrespective of their spatial position within the trawl.

The square mesh window, made of white twisted polyamide 70 mm mesh size and 1.8 mm twine thickness, was positioned above the panel according to Fig. 1. In the present case, blue whiting and horse mackerel, for which there is experimental evidence regarding the effectiveness of square mesh panels (Briggs and Robertson, 1993), were expected to show a positive reaction to the square mesh window since they are, as is the whiting, schooling species with high swimming capacity. Boarfish were also expected to be guided by the panel towards the window. For the remaining fish species, this reaction was expected to be less marked.

The technical drawing of the trawl used is shown in Fig. 2, while Fig. 3 shows the sorting devices and their installation with reference to the trawl upper panel.

A commercial trawl was used, entirely made up of twisted polyethylene 60 mm mesh size, about 47.6 m long and with a circumference of 1242 meshes at the footrope level. During most of the hauls trawl geometry and water speed were monitored by using Scanmar depth, height and spread sensors, and a trawl speed sensor. Visual inspection of the trawl equipped

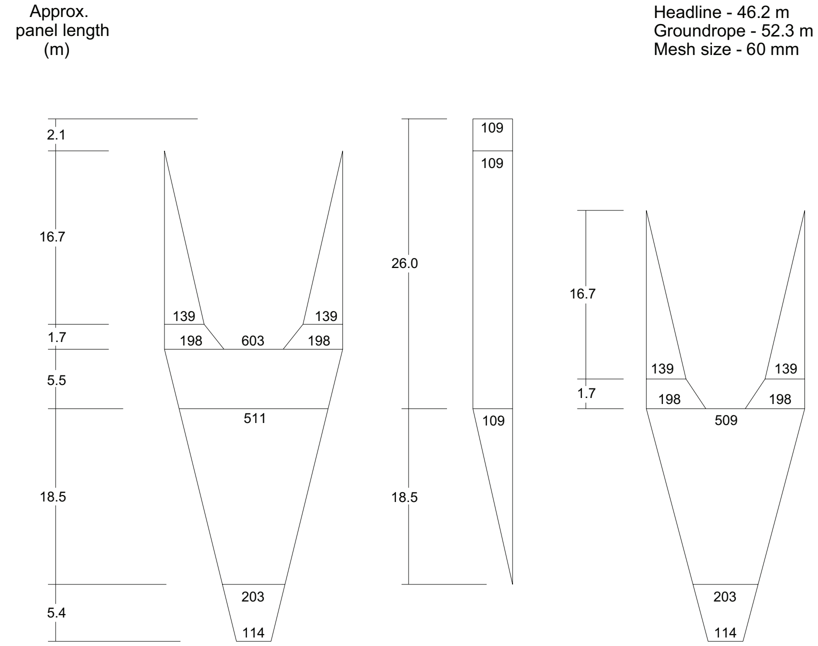

Fig. 2. Technical drawing of the trawl.

with the separator panel was carried out prior to the fishing tests at depths around 50 m, using an underwater video camera installed on a remote operated vehicle (see Campos et al., 1996). In deeper waters, on the crustacean fishing grounds, the visibility was reduced due to high water turbidity generated by the passage of trawl doors and gear over the muddy bottoms, and consequently, no images of the behaviour of crustacean and fish species in relation to the sorting devices could be obtained. A sonar attached to the ROV was also used during the preliminary tests allowing for the recording of trawl geometry in the panel section.

At a trawling speed of approximately 2.5 kn, vertical opening ranged from 1.8 to 2.0 m and wing end spread from 21 to 24 m when the trawl was rigged with 2 m bridles, 70 m sweeps and semi-oval doors with a surface area of 3 m^2 and a weight of 300 Kg. The trawl height at the beginning of the separator panel slightly exceeded 1.5 m, while at the end of the panel it was about 1.4 m. The passage to the lower cod end (given by the distance measured between the trawl lower panel and the separator panel leadline) and the direct access to the upper cod end (measured as the distance between the constrictor rope and the trawl upper panel) were about 25 and 40 cm in length, respectively.

The control of the individuals escaping through the window was made by means of a cover mounted on top of the window. The cover was made of two sections of 1.8 mm twisted polyethylene and 45 mm mesh size, the first section starting before the window and covering it down its full length, while the second section corresponded to a cod end. To minimise masking effects of the cover on the window meshes, the cover was held open by a system of cables and floats. Details of all cod ends used (trawl cod ends and cover cod end) are given at Table 1.

2.2. Data collection

The data were collected during two sea trials carried out off the south coast of Portugal, on board the R/V “Mestre Costeiro”, a 27 m long stern trawler with 460 hp, and a trip on the F/V "Cidade de Tavira" a 26 m and 500 hp commercial trawler. Fishing areas included commercial fishing grounds between Sagres and Faro (Fig. 4), at depths from 180 to 500 m. Haul

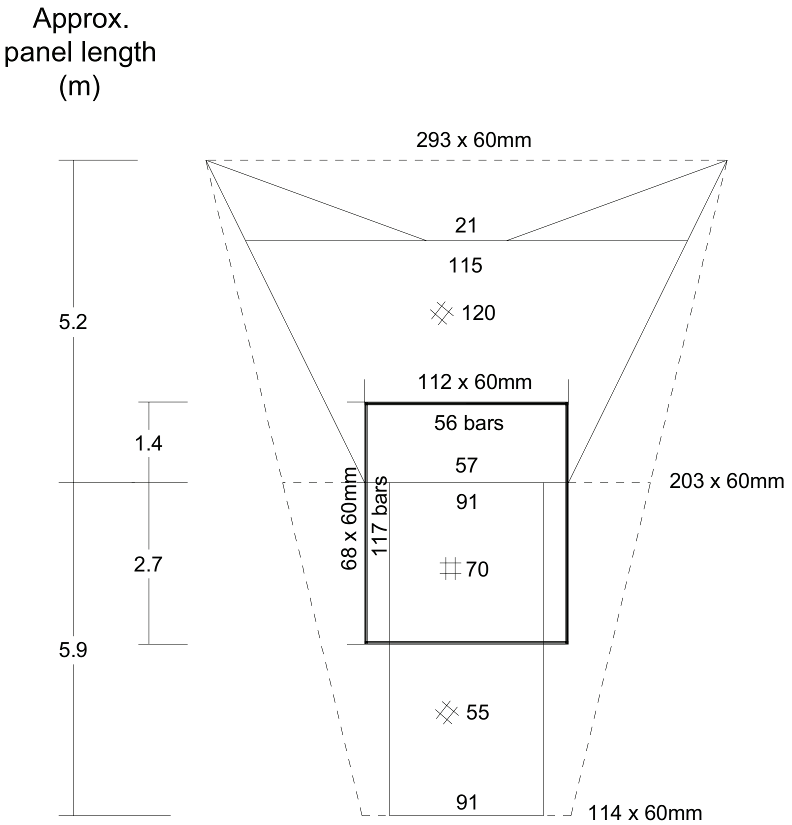

Fig. 3. Technical drawing of the sorting devices and their installation with respect to the trawl upper panel. Dashed lines correspond to the trawl upper panel, thin lines to the separator panel and thick lines to the square mesh window.

Table 1
Details of cod ends.

Cod ends	Material	Mesh size (inside mesh)	Dimensions (nº meshes width x length)	Hanging ratio to trawl panel
Trawl	PE br 4.0 mm	55 mm	200 x 100	1 : 2
Cover	PE tw 1.8 mm	45 mm	250 x 100	1 : 2

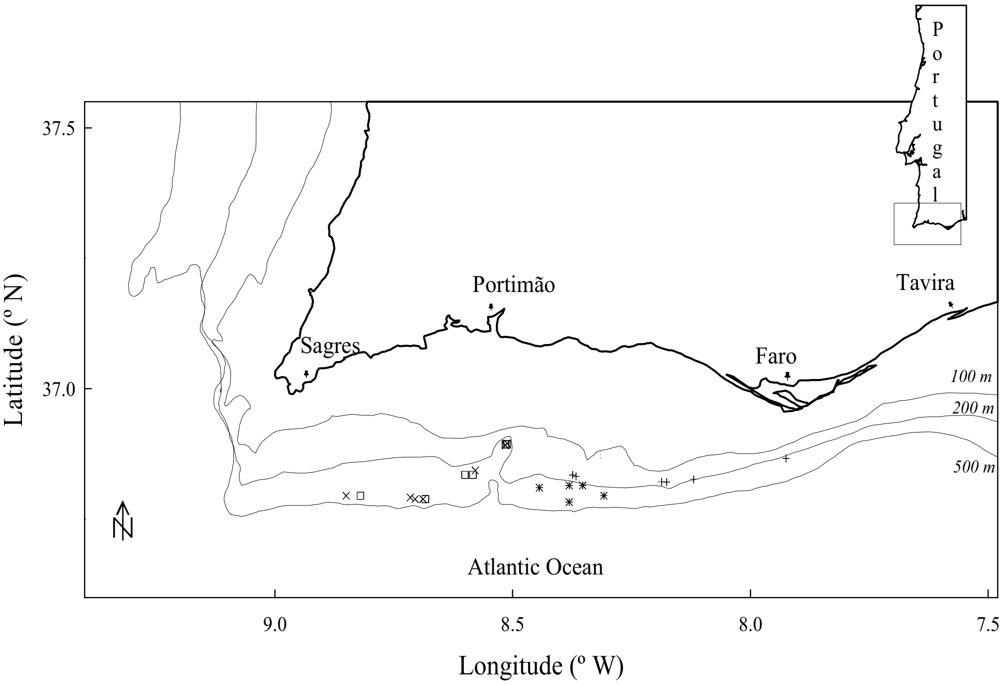

Fig. 4. Location of the hauls carried out with the four different arrangements of the sorting devices. Group 1 (✳); group 2 (+); group3 (×); group 4 (□).

duration varied between 1 h and 3 h 15 m, at trawling speeds between 2.0 and 2.5 kn.

A total of 26 valid hauls were carried out, in which four different arrangements of the sorting devices were tested (Table 2). During the first sea trial, in July 1993, the 120 mm mesh size separator panel and 70 mm square mesh window were tested, while in the commercial trip (September 1993) the square mesh window was replaced by another with the same characteristics but higher mesh size (100 mm). In May 1994 the mesh size in the separator panel forepart was reduced to 80 mm, while in a second phase the separator panel was removed and the 100 mm mesh size window was tested alone.

During the experiments, catches from each cod end (lower, upper and cover) were handled separately on board. Total catch weight was recorded along with the weight of the main target and by-catch species. Carapace length and total length of commercial crustacea and fish (and of blue whiting) were measured to the millimetre and centimetre below respectively, with the exception of the hauls on board the F/V "Cidade de Tavira", where the working conditions on board did not allow for length sampling. Subsampling was carried out in many of the hauls for all the species captured. The length class frequencies for

Table 2
Different arrangements of the sorting system. SP: separator panel; SMW: square mesh window.

Group	Vessel	Date	Nº hauls	Sorting devices tested
1	R/V "Mestre Costeiro"	July 93	6	SP 120 mm + SMW 70 mm
2	F/V "Cidade de Tavira"	Sep 93	6	SP 120 mm + SMW 100 mm
3	R/V "Mestre Costeiro"	May 94	7	SP 80 mm + SMW 100 mm
4	R/V "Mestre Costeiro"	May 94	7	SMW 100 mm

each species in sub-sampled hauls were estimated by scaling up the frequencies in the sub-samples (lower cod end, upper cod end and cover) by the inverse of the sampling proportions.

2.3. Data analysis

The whole sorting system was evaluated as a by-catch excluder for the most important species, by comparing the percentage of the total catch that was excluded (i.e., escaped through the square mesh window) in the different test situations, groups 1 to 4. In addition, the separator panel, as well as the square mesh window, could be evaluated separately. In the first case, this was done by comparing, in groups 1 to 3, the percentage of the total catch reaching the upper level of the trawl, corresponding to the sum of catches in the upper cod end and cover. The evaluation of the square mesh window was made by comparing, also in groups 1 to 3, the catch fraction retained in the cover with that reaching the upper level of the trawl. These catch percentages will be referred to along the text as "*excluded*", "*contact*" and "*excluded after contact*", respectively. For group 4 (panel removed) only the excluded percentage was analysed.

A non-parametric ANOVA (Kruskal-Wallis test (Conover, 1980)) was carried out to test the null hypothesis of no difference between groups. Whenever significant differences were found, a multiple comparison test (Conover, 1980) was used to determine which pairs of groups differed significantly. All the analysis was based on the catch percentages in weight since no information on the numbers of individuals was obtained for group 2, during the hauls carried out on board the F/V "Cidade de Tavira".

Whenever length-dependence was observed for those individuals escaping through the window, the window selectivity was modelled. However, unlike selectivity in cod ends, where the entire population entering is submitted to the selection process, the size-selection by a sorting device such as windows is dependent on whether the fish encounter it. In fact, underwater observations (Glass and Wardle, 1995) have shown that a significant proportion of fish that enter a net equipped with a window may pass below the window without being aware of it. Therefore, the probability $r(l)$ that a fish of length l is retained by the window, i.e., does not escape through the window meshes, was modelled according to the expression:

$$r(l)=\frac{p*\exp(v_1+v_2 l)}{1+\exp(v_1+v_2 l)}+(1-p)$$

(Tokai et al., 1996; Tokai, 1998; Zuur et al., 2001), where $v=(v_1,v_2)^{\mathrm{T}}$ is the vector of selectivity parameters and p accounts for the probability of encountering the window.

3. Results

3.1. Catch data and separation within the trawl

Rose shrimp accounted for a small percentage (between 3 and 13%) of the total catch in weight in all hauls, while Norway lobster attained much higher yields in some of the hauls (Table 3). The boarfish was the most important species in weight in almost all the hauls at depths from 180 to 300 m where the rose shrimp was the target species. In the remaining hauls, below 300 m, yields for rose shrimp were extremely low since it was replaced by the Norway lobster, which was associated with blue whiting in most of the hauls. Fishing yields for horse mackerel were relatively high in some of the hauls at depths from 180 to 300 m, except in group 4, where it was captured in small amounts.

In Tables 4 and 5 the average percentages *excluded*, in *contact* and *excluded after contact* are shown for crustaceans and by-catch species respectively, in numbers and weight, or only in weight for the hauls on board the F/V Cidade de Tavira (group 2). High between-haul variability in these percentages was found for most species/groups, as indicated by the high values for the coefficients of variation.

Possible causes for between-haul variability for the *excluded* within the different groups of hauls were investigated. The percentage excluded for boarfish, the most abundant species, was found to be significantly correlated to the logarithm of species catch size in group 2, and to species catch size in group 4 (Fig.5), where catches varied within a broad range from 20 to 1700 Kg approximately, suggesting that the reaction of these species to sorting devices can be dependent on schooling behaviour. For blue whiting and horse mackerel, much lower catches were

Table 3
Fishing yields (Kg/h) by haul, for the most important species caught.

					Fishing yields (Kg/h)					
Group	Haul nº	Date	Haul duration (h)	Average depth (m)	Total	Rose shrimp	Norway lobster	Horse Mackerel	Blue whiting	Boarfish
1	1	22 July 93	1.00	280	393.7	12.5	2.9	3.2	7.2	345.0
	2	22 July 93	1.00	245	201.7	10.4		30.0	5.6	144.9
	3	22 July 93	1.00	310	52.5	5.1	2.9	2.9	19.1	1.1
	4	22 July 93	1.00	245	328.6	22.5		19.5		270.0
	5	24 July 93	1.00	250	394.6	21.7		20.3	50.0	285.0
	6	24 July 93	2.00	510	27.6		16.4		4.2	
2	7	15 Sep 93	2.50	233	29.0	1.4		12.4	0.4	12.8
	8	15 Sep 93	2.83	180	120.2	3.3		19.8		81.3
	9	15 Sep 93	3.17	197	26.9	3.5		9.8		10.4
	10	16 Sep 93	3.00	198	74.7	5.0		23.3		45.0
	11	16 Sep 93	3.25	183	51.7	3.4		8.9		29.2
	12	16 Sep 93	2.58	200	982.5	4.6		4.7		581.4
3	13	25 May 94	2.00	243	191.3	13.0		8.9	3.1	150.0
	14	25 May 94	1.50	245	392.0	12.2	0.1	106.7	1.7	240.0
	15	25 May 94	1.00	235	197.2	14.6	0.2	52.3	6.0	87.5
	16	26 May 94	3.00	445	40.8	1.7	4.6		25.5	
	17	26 May 94	3.00	435	89.9	1.8	18.6		62.1	0.9
	18	27 May 94	1.00	280	76.0	3.3	37.4	2.9	22.2	2.3
	19	27 May 94	1.00	430	99.6	2.7	17.0	0.8	29.6	27.5
4	20	28 May 94	3.00	435	106.3	1.3	22.9	1.8	14.4	59.3
	21	28 May 94	3.00	430	59.0	1.8	6.0	0.1	38.9	7.5
	22	29 May 94	2.00	235	885.2	19.8		2.7	3.3	847.5
	23	29 May 94	2.00	235	451.3	17.3		2.4	2.1	420.0
	24	30 May 94	2.00	235	448.8	20.4	0.2	2.4	2.9	412.5
	25	30 May 94	2.00	235	228.2	19.8	0.2	5.2	5.4	185.0
	26	30 May 94	2.00	235	319.8	21.8	0.1	3.6	6.0	277.5

Table 4
Crustaceans - Average catch percentages excluded and in contact with the square mesh window, for the different groups of hauls. Coefficients of variation (CV = std/average * 100) are in brackets. All Norway lobsters were above the minimum landing size (MLS).

Groups		Total catch	Lower cod end	Upper cod end	Cover	Average %					
						Excluded		*Contact*		*Excluded after contact*	
						Rose shrimp					
1	Total nº	8150	7072	520	558	6.0	(119%)	12.6	(91%)	40.0	(26%)
	<MLS	3051	2594	135	322	8.2	(136%)	12.9	(108%)	49.2	(46%)
	≥ MLS	5099	4478	385	236	4.4	(91%)	11.9	(83%)	35.8	(17%)
	Kg	72.2	61.4	6.0	4.8	5.6	(116%)	14.2	(83%)	36.5	(35%)
2	Kg	61.8	56.0	2.5	3.3	4.3	(102%)	9.5	(46%)	39.7	(88%)
3	Total nº	7327	3250	1493	2584	27.9	(34%)	56.2	(13%)	50.5	(36%)
	<MLS	3065	1343	519	1203	37.5	(92%)	59.9	(57%)	66.8	(58%)
	≥ MLS	4262	1907	974	1381	26.9	(34%)	55.7	(16%)	49.1	(35%)
	Kg	75.2	34.2	15.7	25.4	27.8	(33%)	55.6	(15%)	50.9	(36%)
4	Total nº	21594	16153		5441	25.1	(31%)				
	<MLS	8106	5788		2318	20.9	(82%)				
	≥ MLS	13488	10365		3123	23.6	(31%)				
	Kg	207.2	156.7		50.5	24.3	(28%)				
						Norway lobster					
1	Total nº	1279	1253	18	8	0.2	(173%)	0.8	(173%)	10.3	(173%)
	Kg	38.6	37.8	0.7	0.2	0.2	(173%)	0.9	(173%)	7.8	(173%)
3	Total nº	4002	2474	1466	62	1.8	(34%)	38.0	(17%)	4.6	(34%)
	Kg	124.2	75.1	47.3	1.8	1.6	(43%)	38.8	(19%)	3.9	(29%)
4	Total nº	2647	2612		35	1.2	(43%)				
	Kg	86.9	86.0		0.9	0.9	(46%)				

Table 5
By-catch species. Average catch percentages excluded and in contact with the square mesh window for the different groups of hauls. Coefficients of variation (CV = std/average * 100) are in brackets. All horse mackerel were above the minimum landing size (MLS), while for blue whiting and boarfish there is no MLS.

Groups		Total catch	Lower cod end	Upper cod end	Cover	Average %					
						Excluded		*Contact*		*Excluded after contact*	
						Horse mackerel					
1	Total nº	913	273	297	343	36.5	(48%)	69.6	(12%)	51.0	(39%)
	Kg	69.8	22.8	25.0	22.0	34.1	(51%)	68.6	(12%)	48.1	(41%)
2	Kg	198.0	107.0	38.0	53.0	33.4	(57%)	51.4	(21%)	60.3	(49%)
3	Total nº	2578	332	366	1880	73.0	(34%)	91.0	(6%)	80.2	(32%)
	Kg	230.2	29.0	37.2	164.0	72.3	(36%)	91.0	(6%)	79.4	(35%)
4	Total nº	292	214		78	28.3	(25%)				
	Kg	37.7	27.8		9.9	26.3	(18%)				
						Blue whiting					
1	Total nº	1002	240	146	616	69.3	(18%)	81.4	(8%)	84.8	(13%)
	Kg	90.2	21.4	11.3	57.6	69.6	(15%)	81.3	(8%)	85.4	(10%)
3	Total nº	1953	81	609	1263	76.1	(17%)	97.3	(4%)	77.9	(15%)
	Kg	326.6	16.0	124.0	186.6	70.9	(20%)	97.1	(4%)	72.8	(19%)
4	Total nº	1305	269		1036	80.9	(14%)				
	Kg	194.8	87.9		106.9	66.9	(25%)				
						Boarfish					
1	Kg	1044.9	260.0	680.0	104.9	9.7	(90%)	77.3	(25%)	12.0	(70%)
2	Kg	2025.0	245.0	350.0	1430.0	41.5	(60%)	67.3	(31%)	56.5	(42%)
3	Kg	775.0	92.0	210.0	473.0	44.2	(63%)	78.8	(21%)	53.0	(49%)
4	Kg	4485.5	3590.0		895.5	16.9	(28%)				

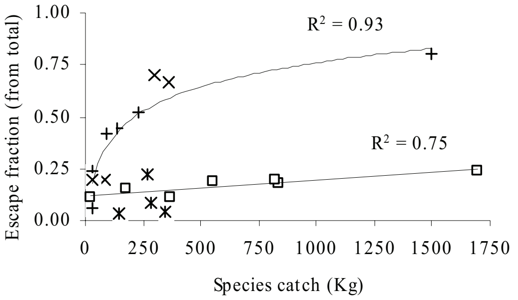

Fig. 5. Relationship between the percentage excluded and species catch in the four groups of hauls, for boarfish. Group 1 (∗); group 2 (+); group3 (×); group 4 (□). R^2 for groups 2 and 4 was found to be significant at $\alpha = 0.05$ (p-values = 0.0018 and 0.0121 respectively).

obtained and therefore such correlations were not estimated. For the crustaceans, between-haul variability, which was evident mainly for group 1, is probably related to the low percentages of exclusion and contact within this group.

Differences observed in some of these percentages when estimated in numbers and weights suggest length-dependence in *contact* with the square mesh window, as well as in *exclusion* (after contact and from total catch). This is particularly noticeable for blue whiting in groups 3 and 4, where the percentages excluded are much higher when based on numbers, denoting a higher escapement of smaller individuals. For rose shrimp, data in Table 4 suggest preferential contact and exclusion of the catch fraction below the minimum landing size (24 mm) in groups 1 and 3.

Fig. 6 shows the length frequency distributions in the different cod ends for rose shrimp, Norway lobster, horse mackerel and blue whiting, in the three groups of hauls corresponding to the testing conditions in Table 2 onboard the R/V “Mestre Costeiro”. Data for blue whiting show that the smaller individuals from 10 to 15 cm captured in groups 3 and 4 were almost entirely excluded from the trawl, being retained by the cover. For horse mackerel exclusion also occurred preferentially for the lower length classes from 16 to 19 cm, in group 1, and from 17 to 23 cm in group 3, while in group 4, where catches were scarce, there was no apparent size-dependence.

3.2. ANOVA

Results of the Kruskal-Wallis and multiple comparison tests, based on weight percentages, are presented in Table 6. Significant differences between groups for the percentage in *contact* with the window were found for all species except the boarfish. Differences from groups 1 and 2, in the case of rose shrimp, (only group 1, for Norway lobster and blue whiting), where the 120 mm mesh size panel was used, were found when these groups were compared to group 3, where the panel mesh size was reduced to 80 mm. The pattern was somewhat different for horse mackerel, for which groups 1 and 3 differed significantly from group 2.

On the other hand, the comparisons using the percentage of *excluded after contact* with the window, do not present significant differences except for boarfish, between group 1 (70 mm window), with low exclusion, and groups 2 and 3 (100 mm window), where the percentage of escapees, of those that came into contact with the window, increased considerably in most of the hauls.

Finally, the analysis of the *excluded* percentages (of the total catch) showed significant differences between groups for the boarfish and in particular the rose shrimp, for which the null hypothesis could be rejected at $\alpha = 0.001$. For the latter species, groups 1 and 2, with low exclusion, were found to be significantly different from groups 3 and 4, where escapement rose to values well above 20% of the total catch. For boarfish, all the comparisons resulted in the rejection of the null hypothesis except those between groups 1 and 4 (low exclusion), and groups 2 and 3, where exclusion attained the highest figures. For the remaining species, Norway lobster, blue whiting and horse mackerel, exclusion was apparently independent of the different panel/window mesh size combinations.

3.3. Size selectivity of the square mesh window

Clear length-dependence was observed for horse mackerel and rose shrimp escapees in group 1 of hauls, where the 70 mm mesh size window was used, and therefore, the encounter probability model was adjusted to the proportions of fish retained by the window (found at the upper cod end) from the total

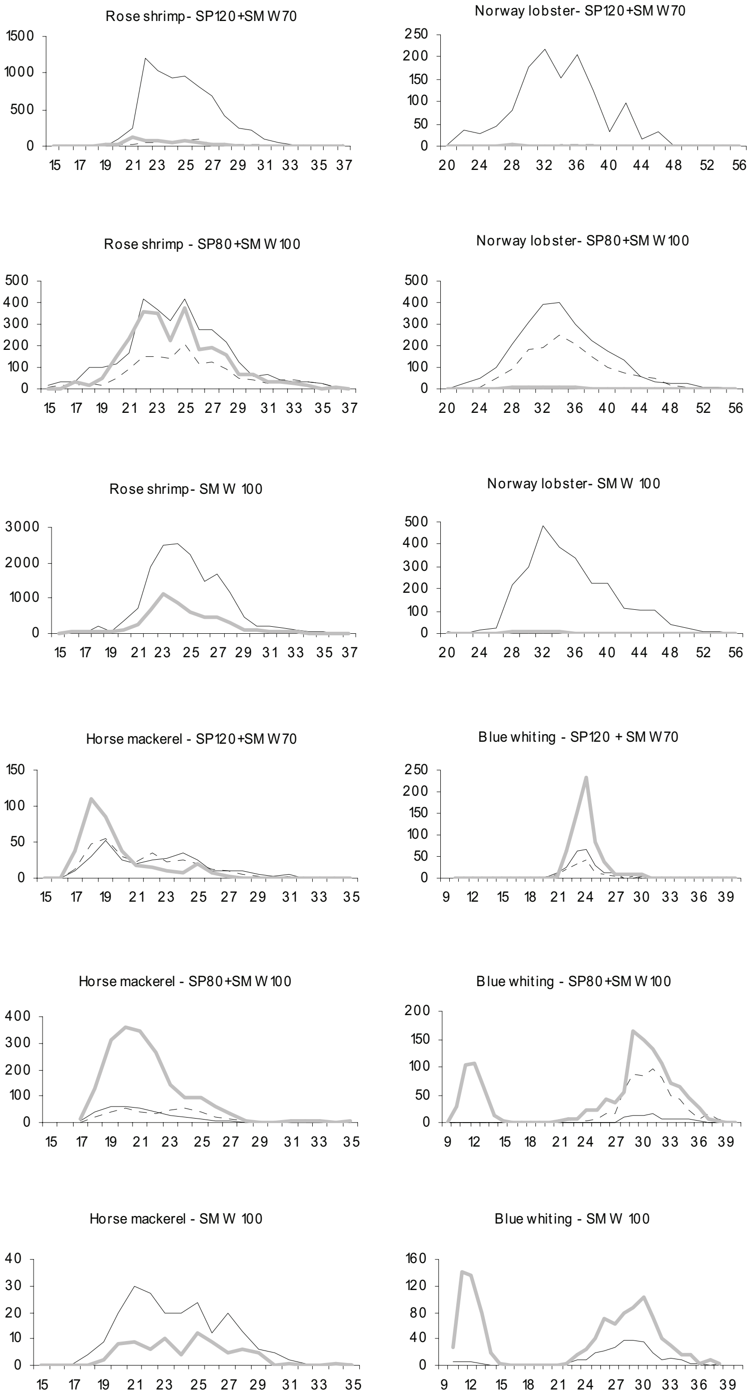

Fig. 6. Size structure of the populations that entered the different cod ends. The thin, dashed and dotted lines correspond to fish retained in the lower cod end, upper cod end and in the cover, respectively. SP – sorting panel; SMW – square mesh window.

Table 6
Results of ANOVA (Kruskall-Wallis test) and multiple comparisons tests.

		Kruskall-Wallis		Multiple comparisons	
	Nº hauls	Groups	p-value	Groups	p-value
		Rose shrimp			
Contact	18	1; 2; 3	0.002	1 vs. 2	0.553
				1 vs. 3	<0.001
				2 vs. 3	<0.001
Excluded after contact	18	1; 2; 3	0.517		
Excluded	25	1; 2; 3; 4	<0.001	1 vs. 2	0.711
				1 vs. 3	<0.001
				1 vs. 4	<0.001
				2 vs. 3	<0.001
				2 vs. 4	<0.001
				3 vs. 4	0.521
		Norway lobster			
Contact	7	1; 3	0.049		
Excluded after contact	7	1; 3	0.593		
Excluded	9	1; 3; 4	0.059		
		Horse mackerel			
Contact	12	1; 2; 3	0.013	1 vs. 2	0.013
				1 vs. 3	0.052
				2 vs. 3	<0.001
Excluded after contact	12	1; 2; 3	0.281		
Excluded	18	1; 2; 3; 4	0.077		
		Blue whiting			
Contact	11	1; 3	0.008		
Excluded after contact	11	1; 3	0.178		
Excluded	17	1; 3; 4	0.790		
		Boarfish			
Contact	14	1; 2; 3	0.662		
Excluded after contact	14	1; 2; 3	0.027	1 vs. 2	0.006
				1 vs. 3	0.009
				2 vs. 3	0.934
Excluded	21	1; 2; 3; 4	0.025	1 vs. 2	0.006
				1 vs. 3	0.009
				1 vs.4	0.266
				2 vs. 3	0.939
				2 vs. 4	0.032
				3 vs. 4	0.046

catch at the upper trawl level (upper cod end + cover). For both species, p was estimated to be 1, and therefore escapement was found to follow a logistic model with parameters v_1 and v_2. This seems to indicate that all the fish reaching the upper level of the trawl encountered the window. The selectivity parameters estimated are presented at Table 7, while Fig. 7 shows the selection curves plotted together with the observed retention values.

For the 100 mm mesh size windows no modeling of the escape was possible due to much less obvious length-dependence in retention, with the bigger mesh size allowing for a higher proportion of larger fish to escape.

Table 7
Selectivity parameter estimates for horse mackerel and rose shrimp escaping through the 70 mm square mesh window. v_1 and v_2 are the estimated selectivity parameters; R the respective variance matrix; $L_{50} = (-v_1 / v_2)$; SR = (2 ln(3) / v_2) ; SF = L_{50} / mesh size ; CI are confidence intervals for L_{50} and SR.

Selectivity estimates	Horse mackerel (3 hauls)	Rose shrimp (5 hauls)
Retained		
<MLS	0	135
≥ MLS	307	385
Escapees		
<MLS	0	322
≥ MLS	347	236
v_1	-5.071	-6.555
v_2	0.237	0.260
R_{11}	0.898	1.542
R_{12}	-0.0427	-0.0613
R_{22}	0.00206	0.00246
L_{50} (cm or mm)	21.4	25.2
L_{25} (cm or mm)	16.8	21.0
L_{75} (cm or mm)	26.1	29.5
CI L_{50} (cm or mm)	20.3 - 22.6	24.1 - 26.4
SR (cm or mm)	9.3	8.5
CI SR (cm or mm)	5.3 - 13.3	5.0 - 11.9
SF	3.1	0.360
Deviance	19.6	59.8
Df	10	14
p-value	0.0337	0.0000

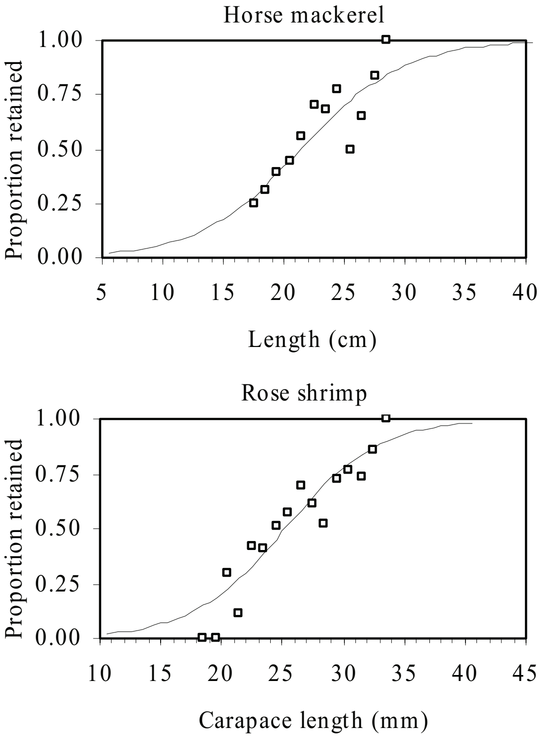

Fig. 7. Selectivity curves (pooled data) for horse mackerel and rose shrimp in the 70 mm square mesh window, estimated from the catch fraction retained after reaching the trawl upper level. Observed retention is indicated by squares.

4. Discussion

Data obtained for the four panel/window combinations allow inferences to be made concerning the behaviour of the different species towards the whole sorting system, as well as the different components. The percentages of the catch in *contact* with the square mesh window (catch in the upper cod end plus cover/total catch), suggest differences in boarfish behaviour induced by the separator panel when compared with the other species. In fact, boarfish were equally concentrated in the upper level of the trawl, under the area of influence of the square mesh window, independently of the panel mesh size, while for blue whiting and the crustaceans the percentage in *contact* with the window was significantly higher when the panel mesh size was reduced from 120 to

80 mm. The fact that the latter situation originated much higher concentrations in the upper level of the trawl, suggests that the reduction in the panel mesh size resulted in a physical constraint to the passage of these species through the panel, indicating that the access of Norway lobster to the lower cod end was not confined to the gap between the separator panel forepart and the lower belly, as previously anticipated, but that a certain fraction of the catch can cross the panel if the meshes are large enough.

The percentage of *excluded* after having been in *contact* with the window (catch in the cover/catch in the upper cod end plus cover) can be seen as a measure of the ability of a given species to escape through the window, since all the individuals at the upper cod end and the cover had been in direct contact with the window, or at least within its area of influence. For boarfish, statistically significant differences were found in the weight percentage of *excluded after contact* associated with the increase in window mesh size from 70 to 100 mm, indicating that the smaller mesh size represented a physical constraint to the escape of this species. This was not observed for the remaining species, including the blue whiting. However, a clear length-dependence was observed for horse mackerel and rose shrimp escapees when the 70 mm mesh size was used, allowing for the estimation of window selectivity parameters.

Finally, the percentage of *excluded* from the total catch provides an insight on the behaviour of the different species to both sorting devices together constituting a selective system. Here, significant differences in exclusion among groups were found only for rose shrimp and boarfish.

The fact that no differences in escapement were detected for the Norway lobster between groups 1, 3 and 4 reflects the fact that the Norway lobster is essentially passive, with experience showing that it only reacts when in direct contact with a gear component (Newland et al., 1988; Newland and Chapman, 1989).

For blue whiting, the high percentage of escapees did not differ significantly between groups 1 and 3, despite the fact that the reduction in the separator panel mesh size, separately considered, was found to be associated with an increase in the amount of fish in *contact* with the window. Moreover, the fact that group 4 (no panel installed) did not differ significantly from the other two is a further indication that this species is the only one presenting an active escape behaviour.

For rose shrimp, these data provide us with strong evidence that the differences found in *excluded* are related to an increase in *contact* due to the reduction in panel mesh size from 120 to 80 mm. The non-existence of significant differences between groups 3 and 4 is more difficult to explain, since the panel removal was expected to reduce the amount of the catch in contact with the square mesh window, and thus lower the escapement.

For boarfish, on the other hand, the differences in exclusion found between groups seem to be more related to differences in the window mesh size, which is not surprising given that the catch fraction in *contact* with the window was not found to be affected by changes in panel mesh size. There is however evidence that *contact* is reduced with panel removal, when comparing groups 3 and 4, where the windows mesh size is the same. Therefore, for boarfish, unlike blue whiting, these data suggest the need for adequate stimuli in order to improve escape behaviour.

Finally, for horse mackerel, the fact that no statistically significant differences were detected between groups, in spite of the large differences in the escape percentage between group 3 and all the others, most probably reflects the high between-haul variability in the exclusion percentage within each group.

Comparison of the selectivity parameters estimated within this work for the 70 mm square mesh window with previous estimates for horse mackerel (Campos et al., 2003) and rose shrimp (Campos et al., 2002) in 55 mm square mesh cod ends indicates lower selectivity for both species, as can be observed by the lower values for SF (3.1 and 0.36 respectively) when compared to previous values (3.9 and 0.48). The small area covered by the window when compared to the cod end area, as well as its forward position in relation to cod end, might explain the differences in selectivity to a high extent.

Overall, these experiments demonstrated that the best results in terms of excluding the non-commercial species while keeping commercial catches of crustaceans were obtained when the separator panel of 120 mm mesh size was used together with the 100 mm square mesh window. Even considering that blue whiting and Norway lobster were not captured in this group of hauls, the results obtained for the other groups allow the assumption that the increase in window mesh size from 70 to 100 mm would not affect escapement for these two species. Therefore, it can be concluded that for blue whiting the exclusion would attain similar values to those in group 1, around 70%, which is slightly above the figures obtained in cod end selectivity experiments by Campos et al. (2003) when using the 70 mm diamond mesh cod end. The mean value found for the exclusion of boarfish (42%) is, on the other hand, slightly lower than in the previous experiments. However, a catch effect was found in boarfish exclusion, which attained 80% of the total catch in one haul within group 2. Losses of rose shrimp in this group were very low (4.3%).

No previous experiments are reported where sorting panels of this type were used together with square mesh windows. However, square mesh windows alone have been tested immediately before the cod end extension (Armstrong et al., 1998) or in the extension (Thorsteinsson, 1991; Robertson and Shanks, 1994). Although the results reported by these authors are not directly comparable with ours, since they essentially compare mean catch rates in experimental and standard trawls using twin-trawl rigging systems, Robertson and Shanks (1994), using a square mesh window 3 metres long and 80 mm mesh size reported mean weight catches of whiting in experimental trawl within the range of 42 to 46% of those obtained in the standard trawl, while for the Norway lobster no differences in mean catches were recorded. Their results do not differ much from those obtained for blue whiting and Norway lobster in the present study when the square mesh window was used alone, where the average percentage of blue whiting excluded was 67%, and total retention was observed for the Norway lobster.

Between-haul variability in the percentage of *excluded*, was in part attributed to schooling behaviour for boarfish, where escapement was found to increase with species catch size for groups 2 and 4 (see Fig. 5). For all the other species, catches were too low or their range too small to look for effects of this variable.

However, it is conceivable that, given that the separator panel is a flexible structure, differences in panel geometry could have occurred between hauls, which can be partially responsible for differences in separation of the individuals inside the trawl.

5. Conclusions

The number of hauls with the different panel/window combinations is low and therefore these results must be carefully considered. However, the fact that the exclusion of boarfish, the most important by-catch species during the experiments, attained values of 75%, with acceptable losses of shrimp and virtually no losses of Norway lobster, was particularly important since boarfish is a small spiny fish, making the catch separation on board an extremely difficult and time-consuming task and lowering the quality of crustaceans. Therefore, the use of the sorting devices tested would greatly contribute to reducing the time spent separating the catches on deck and improving the quality of crustacean and commercial fish captured.

Furthermore, the mesh size used in both trawl cod ends during these experimente was 55 mm. The increase in mesh size of the upper cod end would certainly contribute to minimize the catch of undersized commercial fish species.

In spite of the good results obtained, the complex design and installation of oblique separator panels such as the ones tested are thought to be two major drawbacks for their commercial introduction in Portuguese fisheries. Panel installation is a complex process, involving scale tests in flume tank and further sea trials where trawl geometry must be carefully checked out, preferably by means of direct observations.

On the other hand, the use of a square mesh window alone proved to be efficient in excluding the blue whiting, although not boarfish, a fact that has been confirmed by a latter study (Campos and Fonseca, unpublished). Given the simple construction, low-cost and fast and easy fitting, their use as by-catch reducing devices poses no major drawbacks and should be seriously considered. More recently, Fonseca et al. (unpublished data) demonstrated that the use of grids can also effectively contribute to lowering the huge discard rates, which take place in the crustacean trawl fishery. Hence, there is a significant potential for the use of by-catch reducing devices in this fishery.

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Reduction of unwanted by-catch in the Portuguese crustacean trawl fishery through the use of square mesh windows placed in the cod end and trawl belly

Aida Campos, Paulo Fonseca

IPIMAR, Portuguese Institute for Fisheries and Sea Research, Avenida de Brasília, 1449-006, Lisbon, Portugal

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Abstract

The utility of square mesh windows as by-catch excluders when placed either in the trawl upper belly or at the top of the cod end is examined for a number of species captured off the Portuguese south coast. Data were obtained for the blue whiting *Micromesistius poutassou*, the boarfish *Capros aper*, the horse mackerel *Trachurus trachurus*, the blue jack mackerel *Trachurus picturatus*, the chub mackerel *Scomber japonicus*, the European hake *Merluccius merluccius* and the rose shrimp *Parapenaeus longirostris*. Active escape behaviour was evidenced for blue whiting and blue jack mackerel, these being the only species escaping in significant amounts, particularly when the square mesh window was placed on the top of cod end. For the remaining fish species, the data suggest the need for appropriate stimuli in order to improve escape behaviour.

Keywords: Trawl selectivity, By-catch reduction devices, Square mesh windows, *Micromesistius poutassou*, *Capros aper*, *Trachurus trachurus*, *Trachurus picturatus*, *Scomber japonicus*, *Merluccius merluccius*, *Parapenaeus longirostris*, Portuguese continental waters

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1. Introduction

The utility of square mesh windows as trawl by-catch reduction devices has been examined worldwide during the past decade, particularly in EU countries. They have been recognized as preferential zones of escape when placed in the cod ends or in other strategically chosen trawl areas, creating visual stimuli that enhance fish escapement (Briggs and Robertson, 1993; Glass et al., 1993) and modifying the water flow inside the trawl (Broadhurst et al., 1999). Square mesh windows have been mainly tested in *Nephrops norvegicus* fisheries to exclude the by-catch of species such as haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus* (Arkley, 1990; Ulmestrand and Larsson, 1991; Briggs, 1992; Thorsteinsson, 1992; Robertson and Shanks, 1994; Armstrong et al., 1998; Madsen et al. 1999) as well as in haddock and whiting fisheries (Ferro, 1991; Hillis et al., 1991). Their potential as by-catch excluders made their use mandatory in Irish and UK *Nephrops* fisheries. More recently, the use of square mesh windows was incorporated in the European Union legislation, as top windows with the aim of allowing the escape of fish by-catch in crustacean fisheries (Council Regulation 850/98) or cod end side windows for Baltic Sea cod fisheries (Council Regulation 3362/94).

The improvement of the selectivity of a commercial trawl equipped with a 100 mm square mesh window, aiming at the exclusion of fish by-catch in the crustacean fishery off the coast of Algarve, was previously addressed by Campos and Fonseca (Paper V) during a short experiment in May 1994, using a square mesh window of 100 mm mesh size placed in the trawl upper belly, 3.3 m before the cod end joining row. Blue whiting (*Micromesistius poutassou*) was the only species for which active escape behaviour was recorded, attaining a mean escape rate of 67% of the total weight per haul. For the rose shrimp (*Parapenaeus longirostris*), one of the target species in this fishery, high losses were reported with 24% of escapees above the minimum landing size of 24 mm.

These results, although based on a small number of hauls, suggest that the huge amount of by-catch in crustacean trawling may be reduced by the use of square mesh windows, provided that losses of target species are minimized. For this purpose, further studies were carried out placing the windows either in the top panel of the trawl or on the top of the cod end. Data herein presented describe the effectiveness of both arrangements in the exclusion of the main by-catch species.

2. Materials and methods

The data were collected during an experiment carried out off the south coast of Portugal from 14 to 21 April 1998, on board the R/V "Noruega" from IPIMAR, a 1500 hp stern trawler. Altogether, 23 valid hauls with duration of 1 h each were carried out during the day in rose shrimp fishing grounds, between Lagos in the west and Tavira in the east, at depths from 200 to 375 m (Fig. 1). The trawl used (Fig. 2) was made up of twisted polyethylene, had a length of about 48.5 m from the wing tips to the cod end joining row, and a circumference of 608 meshes of 140 mm at the footrope level. Headline height ranged from 2.4 to 2.7 m and wingend spread from 21 to 27 m, as measured by Scanmar equipment, when the trawl was rigged with 100 m bridles and semi-oval doors of 650 Kg and was trawled at approximately 3.0 to 3.5 kn. A cod end made of 20 mm mesh size twisted polyamide was used in order to retain the entire catch size range.

Two different windows of 100 mm mesh size made of white twisted PA 2.0 mm diameter were tested. Technical drawings of the square mesh windows and details of the installation are given in Fig. 3. In the first 12 hauls, a window with dimensions of 37 x 60 bars in width and length respectively was placed in the trawl upper panel 3.3 m before the cod end (SMW 1), while in the following 11 hauls (SMW 2) a smaller window of 28 x 40 bars was placed in the cod end top panel, 0.5 m after the cod end joining row. Control of the number of individuals escaping through the square mesh windows was achieved by means of a top cover of 45 mm mesh size in twisted PET, according to technical specifications in Wileman et al. (1996). The cover ended in a collecting bag of the same characteristics as the cod end.

After hauling up, catches from cod end and cover were handled separately and weighed. Carapace length and total length were measured for rose shrimp and for the most important fish species (except the boarfish), to the millimetre and centimetre below respectively. For blue jack mackerel (*Trachurus picturatus*), chub mackerel (*Scomber japonicus*) and the European hake (*Merluccius merluccius*), the whole catch was always measured, while for the remaining species, caught in greater numbers, sub-sampling was carried out in most of the hauls. The length class frequencies for each species in sub-sampled hauls were estimated by scaling up the measured frequencies in the sub-samples (cod end and cover) by the inverse of the sampling proportions.

A Wilcoxon rank-sum test (Conover, 1980) was used to evaluate the significance of the differences between the escape proportions (in weight and in number) for the species studied, for the two groups of hauls, herein referred to as SMW1 and SMW2.

3. Results

General information on the hauls and catches can be found in Table 1. Blue whiting was the most important species in weight in most hauls, particularly those for depths below 300 m, followed by the horse mackerel, which was significantly caught only in a small number of hauls. A large catch of boarfish was recorded only once, while the remaining species were scarcely represented in the catches. Rose shrimp, for which catches in numbers were high, accounted for just a small percentage of the total catch weight in 16 out of the 23 hauls carried out (Table 1).

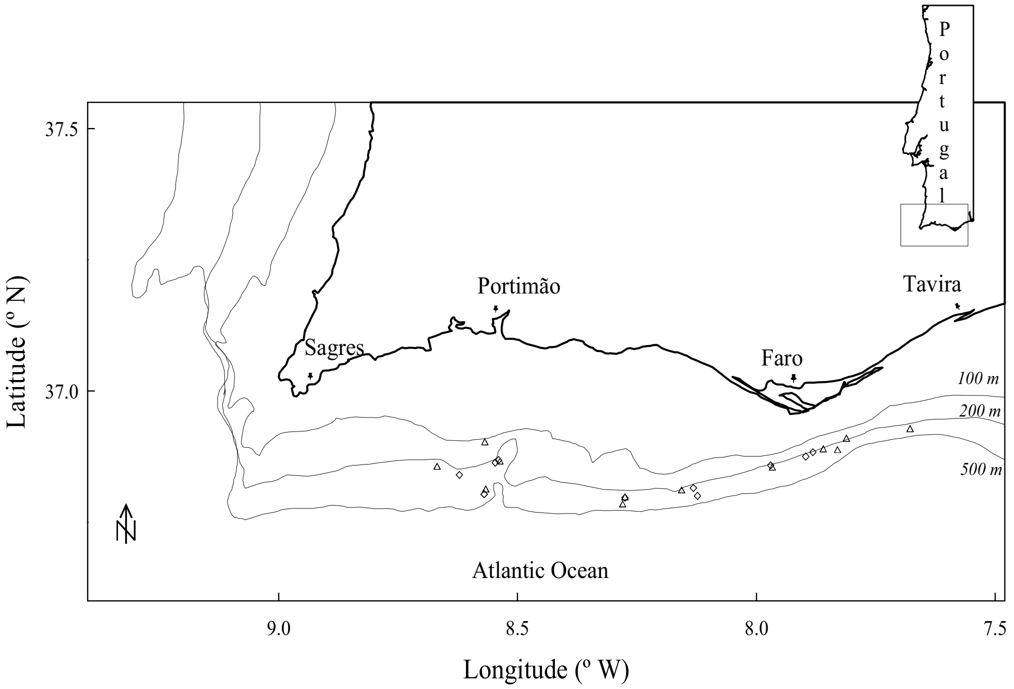

Fig. 1. Location of the fishing hauls. SMW1 (△); SMW2 (◇).

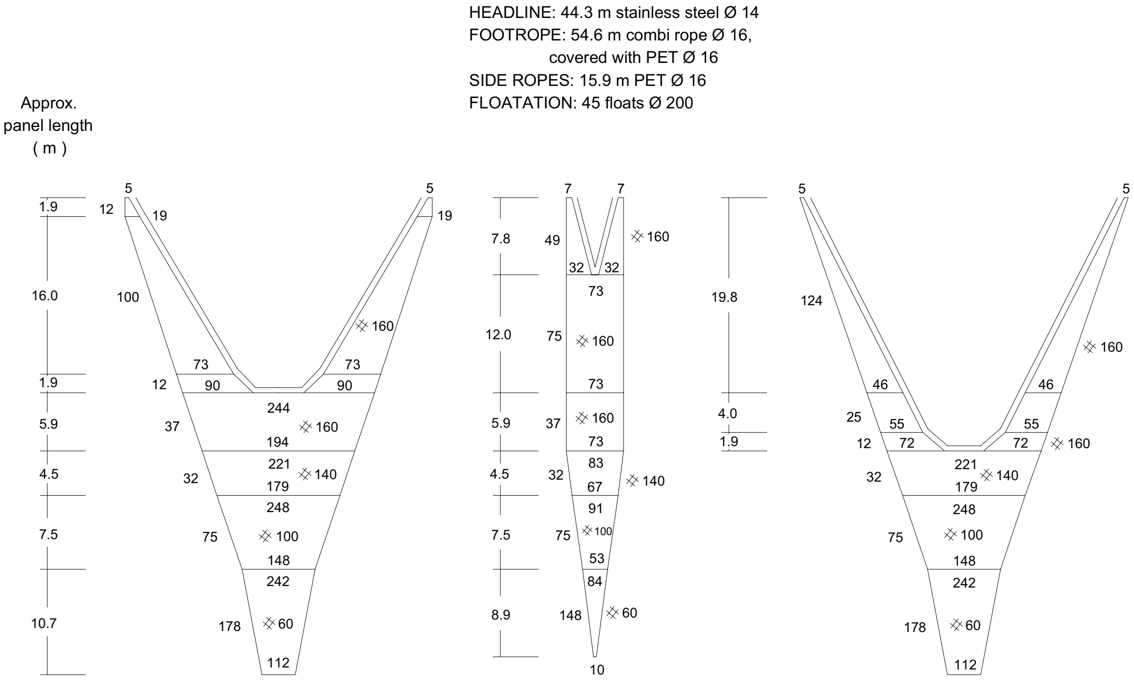

Fig. 2. Technical drawing of the trawl.

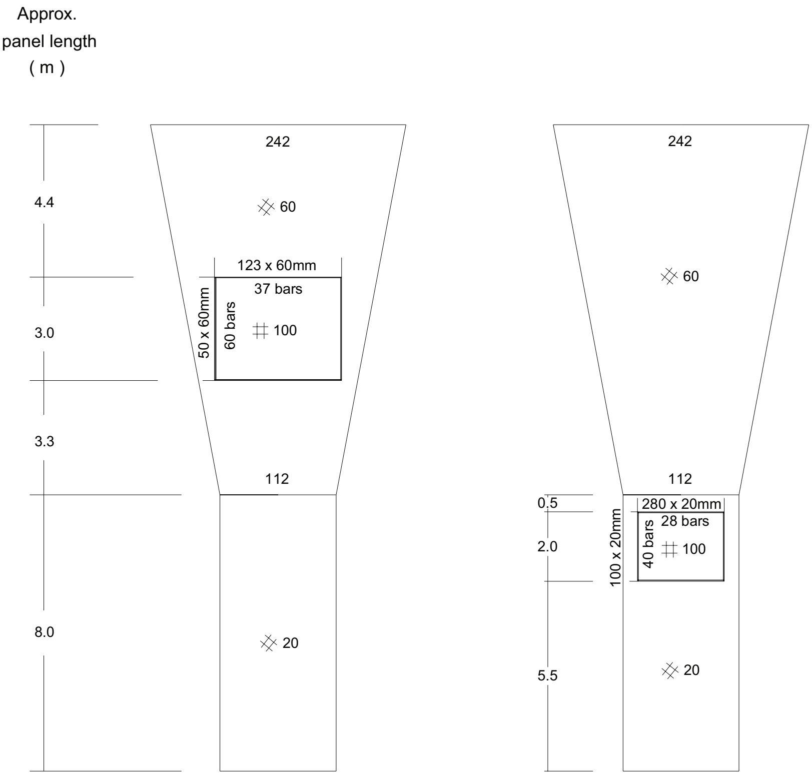

Fig. 3. Technical drawings of the square mesh windows and their installation in the trawl.

Table 1
Fishing yields (Kg/h) by haul, for the most important species.

					Fishing yields (Kg/h)						
Group	Haul nº	Date	Average depth (m)	Total catch (kg)	Rose shrimp	Blue whiting	Boarfish	Horse Mackerel	European hake	Mackerel	Blue jack mackerel
SMW1	1	14 Apr 98	225	595	1.3	39.0	449.0	50.3	19.0	32.0	4.3
	2	15 Apr 98	241	102	2.7	2.1	26.7	17.2	22.5	23.3	3.3
	3	15 Apr 98	321	419	3.6	152.0		200.4	23.5	29.8	8.9
	4	15 Apr 98	225	173	2.3	19.3	33.4	49.4	26.7	29.1	5.3
	5	16 Apr 98	304	112	2.6	103.0		3.5	1.6	1.8	
	6	16 Apr 98	373	59	2.5	56.0			0.8		
	7	16 Apr 98	262	100	8.9	18.0	70.1	0.3	3.0		
	8	16 Apr 98	213	19	9.4	0.2		0.9	2.0	6.1	
	9	17 Apr 98	212	106	39.0	36.0		0.3	30.5		
	10	17 Apr 98	255	68	24.0	6.0		0.2	37.4		
	11	18 Apr 98	341	370	4.1	365.0		0.6			
	12	18 Apr 98	284	51	22.2	7.9		0.9	20.0	0.4	
SMW2	13	19 Apr 98	218	136	18.5	46.0	34.0	2.3	29.6	5.1	
	14	19 Apr 98	204	28	9.4	9.8		3.3	5.4	0.1	
	15	19 Apr 98	217	54	25.5	2.3		4.4	20.7	0.7	
	16	19 Apr 98	252	56	8.5	2.1	42.8	0.5	2.1		
	17	20 Apr 98	364	17	2.9	11.8			0.9		
	18	20 Apr 98	300	31	7.9	20.3		0.3	2.5		
	19	20 Apr 98	324	173	2.2	162.0		5.6	3.5		
	20	20 Apr 98	253	581	2.9	483.0		78.1	10.2	0.2	6.5
	21	20 Apr 98	228	233	5.5	196.0		17.2	13.2		1.3
	22	21 Apr 98	236	206	4.1	91.0		71.0	12.8	7.9	11.0
	23	21 Apr 98	343	166	2.4	127.5		30.8	2.0	1.5	1.7

Fig. 4 shows the length frequency distributions in the cod end and cover for the different species, together with the observed escape proportions, using pooled data from the two groups of hauls corresponding to the different window positions (SMW1 and SMW2). The length distributions for all species were approximately the same in both groups, while changes in the abundance between groups can be seen for blue whiting, caught in much greater numbers in SMW2 hauls, and for both the horse mackerel and the mackerel, for which catches were much greater in SMW1.

The average escape rates are presented in Table 2. Relatively high percentages of blue whiting and blue jack mackerel escaped (27 and 20% in weight, respectively) when the square mesh window was placed in the trawl rear belly, before the cod end (SMW1), while 11% escapement was recorded for rose shrimp. The use of the square mesh window in the cod end (SMW2) substantially improved these figures for both fish species, with average escape percentages of 54 and 48%, without increasing the escapement for the rose shrimp. Boarfish, one of the potentially most abundant bycatch species in shallower waters, presented only a 4% exclusion for SMW1 increasing to about 12% for SMW2. These figures are not surprising since this species has previously shown both a lack of escaping behaviour and a

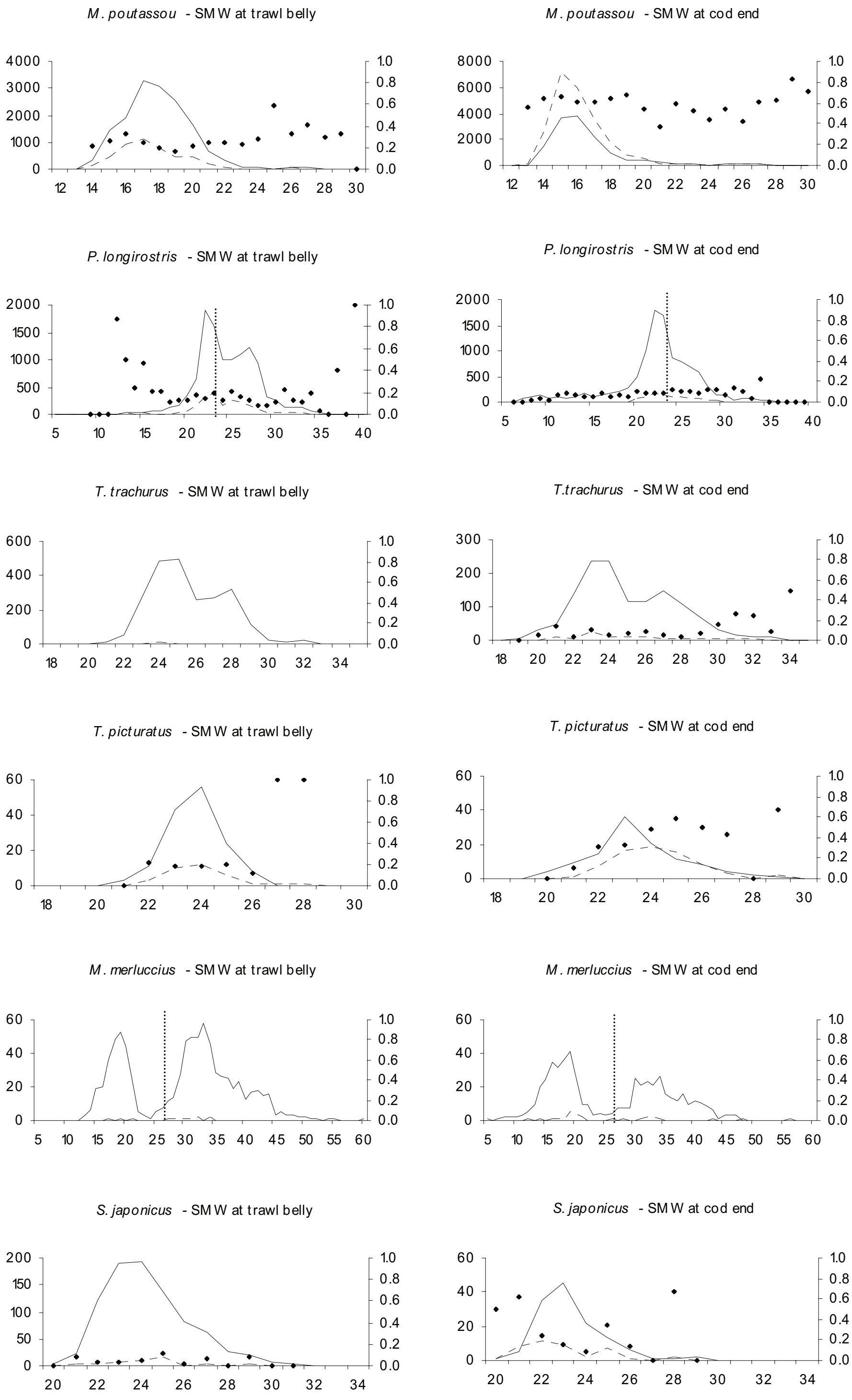

Fig. 4. Size structure of the populations captured along with observed escape fractions. Thin lines correspond to fish retained in the cod end and dashed lines to fish escaping through the square mesh windows. Dotted vertical lines represent the minimum landing size MLS

Table 2

Average catch percentages excluded through the square mesh window, when it was placed in the rear belly (SMW1) and at cod end (SMW2). Coefficients of variation are in brackets. For blue whiting and boarfish there is no MLS, while all horse mackerel, chub mackerel and blue jack mackerel caught were above the respective MLS's.

Groups	Nº hauls		Total catch	Retained	Escapees	Average escape (%)	
			Rose shrimp				
SMW1	12	Total nº	13455	11373	2082	11.1	(69%)
		<MLS	6025	4992	1033	9.3	(103%)
		≥ MLS	7430	6381	1049	10.8	(73%)
		Kg	122.5	104.7	17.7	11.0	(63%)
SMW2	11	Total nº	11416	10379	1037	7.9	(50%)
		<MLS	7195	6614	581	8.6	(107%)
		≥ MLS	4221	3765	456	9.1	(52%)
		Kg	89.7	80.5	9.2	10.6	(63%)
			Blue whiting				
SMW1	10	Total nº	20377	15562	4815	26.8	(47%)
		Kg	802.2	627.5	174.7	26.6	(46%)
SMW2	9	Total nº	37147	13866	23281	54.0	(31%)
		Kg	1147.4	472.3	675.1	53.5	(25%)
			Boarfish				
SMW1	4	Kg	579.0	546.0	33.0	3.6	(64%)
SMW2	2	Kg	76.8	68.0	8.8	12.1	
			Horse mackerel				
SMW1	5	Total nº	2343	2327	16	0.8	(127%)
		Kg	320.8	318.5	2.3	1.0	(115%)
SMW2	5	Total nº	1388	1293	95	8.0	(38%)
		Kg	202.6	189.2	13.4	8.0	(40%)
			European hake				
SMW1	7	Total nº	733	721	12	1.4	(103%)
		<MLS	210	207	3	1.9	(196%)
		≥ MLS	523	514	9	1.3	(107%)
		Kg	179.5	177.5	2.0	1.0	(104%)
SMW2	6	Total nº	477	454	23	5.8	(66%)
		<MLS	232	218	14	8.0	(119%)
		≥ MLS	245	236	9	3.9	(140%)
		Kg	91.8	87.8	4.0	5.3	(78%)

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Table 2 (continued from previous page)
Average catch percentages excluded through the square mesh window, when it was placed in the rear belly (SMW1) and at cod end (SMW2). Coefficients of variation are in brackets. For blue whiting and boarfish there is no MLS, while all horse mackerel, chub mackerel and blue jack mackerel caught were above the respective MLS's.

Groups	Nº hauls		Total catch	Retained	Escapees	Average escape (%)	
			Chub mackerel				
SMW1	5	Total nº	894	846	48	7.6	(115%)
		Kg	120.3	116.8	3.5	3.3	(89%)
SMW2	2	Total nº	139	111	28	22.9	
		Kg	13.0	10.5	2.5	21.5	
			Blue jack mackerel				
SMW1	4	Total nº	179	145	34	20.7	(49%)
		Kg	21.7	17.8	3.9	19.7	(46%)
SMW2	4	Total nº	184	111	73	46.3	(54%)
		Kg	20.6	12.0	8.6	48.2	(53%)

body shape poorly adapted to the square mesh configuration (Paper V). Horse mackerel and hake escape in both situations was almost negligible (1% in SMW1 increasing to 8.0 and 5.3% for SMW2, respectively). Finally, the chub mackerel which had an escape percentage of 3% for SMW 1 attained 22% in the more confined space of the cod end (SMW2).

A high between-haul variability in exclusion was found for all species in both groups of hauls, particularly for SMW1, as indicated by the values for the coefficients of variation in Table 2. The existence of a relationship between the escape percentages and species catch size (in numbers) for the different hauls was investigated within both groups. The percentage excluded was found to be significantly related to the logarithm of catch size, for SMW2 (Fig. 5) for blue whiting, the most captured species. No clear relationship between escapement and catch size was found for SMW2. For the remaining species, much lower catches were obtained and therefore such correlations were not estimated.

Table 3 shows the results of Wilcoxon rank-test comparing the exclusion in the two groups of hauls. Significant differences ($p<0.05$) between groups, both in numbers and weight, were found for blue whiting, as well as for horse mackerel and hake, while for blue jack mackerel the estimated p-values were close to the confidence limit of $\alpha = 0.05$.

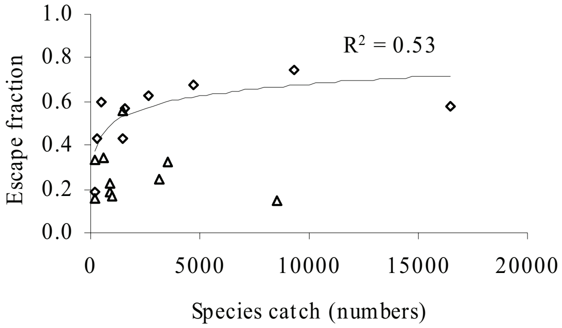

Fig. 5. Relationship between the escape fraction of blue whiting and species catch in the two groups of hauls SMW1 (△) and SMW2 (◇). R^2 for SMW2 was found to be significant at $\alpha = 0.05$ (p-value = 0.026).

Table 3
Results of Wilcoxon rank-sum test comparing escapement in the two groups of hauls.

	Nº hauls		p-value	
Species	SMW1	SMW2	numbers	weight
Rose shrimp	12	11	0.4865	0.9759
Blue whiting	10	9	0.0015	0.0021
Horse mackerel	5	5	0.0079	0.0079
European hake	7	6	0.0260	0.0373
Blue jack mackerel	4	4	0.0571	0.0571

4. Discussion

For all species except the rose shrimp, escapement through the window increased when it was placed in the top of the cod end. This suggests that most fish entering the net with the window placed in the trawl belly passed below it without making any attempt to escape, while in the more confined space of the cod end a greater proportion of individuals either reacted to or were forced into direct contact with the square meshes. On the other hand, as has long been recognized (Boddeke, 1996) shrimps are poor swimmers, showing no active escape behaviour. They are taken passively towards the codend, only displaying a reaction (jumping in a random direction) when they come into contact with the mesh panels. This (lack of) behaviour results in a selection essentially by passive filtering, which may contribute to explaining the similar escape rates in both situations.

Blue whiting and blue jack mackerel were the only species that apparently exhibited active escape behaviour, which was enhanced when the square mesh window was placed in the top of the cod end. For the remaining species escapement was in general low in both situations, although for horse mackerel and hake significant differences were found between SMW1 and SMW2. Chub mackerel was an exception with a low escape rate of 3% in SMW1, with considerable increase to about 22% in SMW2. Even though the relatively low catches may have contributed to this poor outcome, the results obtained were somewhat unexpected for horse mackerel and chub mackerel, two pelagic species with a good swimming performance, particularly the former, for which there is experimental evidence regarding the effectiveness of square mesh panels (Briggs, 1992). For hake, the lack of escape behaviour confirms previous observations in Namibian waters for the two closely related species *Merluccius capensis* and *Merluccius paradoxus* (Isaksen, pers. comm.).

High between-haul variability in escapement was observed for the different species. For most species this may be a consequence of poor sampling. However, for blue whiting, which was caught in large numbers and presents active escape behaviour, the proportion of escapees was positively correlated to species catch, suggesting that the reaction of this species to the window when it was placed at the top of the cod end can be enhanced by schooling behaviour. Similar observations were made by Campos and Fonseca (Paper V) for boarfish escaping from a similar window placed in the trawl belly.

No clear size-dependence was found in escapement, indicating that the 100 mm square mesh window is too large to induce a differential escape by length for these species within the length range captured. On the other hand, for blue jack mackerel a clear pattern is noticed when the window was placed in the cod end, with a higher escape fraction, of up to about 0.6, for larger individuals. Although based on small numbers of individuals, this pattern suggests a behaviour-induced mechanism, with the larger individuals being more able to react to the square mesh window and swim across the meshes.

Comparison of the present data for SMW1, with previous data reported by Campos and Fonseca (Paper V) where the characteristics and the position of the window were similar, evidences a higher escapement for all the common species (rose shrimp, blue whiting, horse mackerel and boarfish) in the previous experiment. It is thought that gear-related characteristics may be on the basis of such differences. The lower vertical opening of the trawl used in previous experiments (less than 2.0 m, vs. 3.0 m in the present work), and thus the more confined space in the trawl rear area, most certainly increased the probability of contact with the square mesh window for the different fish species, thereby enhancing escapement.

The placement of the window in the top of the cod end generally contributed to reducing between-haul variability in escapement, suggesting a more uniform fish behaviour when the fish are confined to the cod end in closer proximity to the window. This reasoning also applies when trying to explain the differences between the figures obtained in SMW1 and group 4 in the previous experiment by Campos and Fonseca (Paper V), where the smaller between-haul variability observed may be a consequence of the lower trawl vertical opening.

5. Final remarks

Overall results indicate that the square mesh windows tested were of little efficiency as by-catch excluders, except for blue whiting, when mounted in the top of the cod end. Furthermore, the 11% loss (in weight) of rose shrimp, although not too high compared to what was verified in other fisheries where square mesh windows were introduced, will probably be perceived as unacceptable by fishermen. On the other hand, escapement was not generally observed to be size-dependent, indicating that the window mesh size was too large for exclusion of undersized individuals both of the target and by-catch species, while maintaining commercial catches. The high vertical opening of the trawl tested in these experiments, possibly decreasing the probability of contact with the square mesh window, can partially explain the poor results obtained for the exclusion of by-catch species. It is suggested that better results could be obtained for blue whiting and horse mackerel with top cod end windows placed in low opening trawls similar to that used by Campos and Fonseca (Paper V). However, escapement of rose shrimp through the window could possibly increase, while boarfish will probably always need appropriate stimuli in order to be excluded.

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