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The effect of grid size on catch efficiency and by-catch in the demersal trawl fishery for Norway pout (*Trisopterus esmarkii*)

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ABSTRACT

Norway pout (*Trisopterus esmarkii*) is caught with large trawls with small meshed codends, inevitably causing the fishery to have large by-catch issues. To reduce the amount of by-catch, a rigid sorting grid was made compulsory in 2010. However, there is still a severe by-catch issue, as well as the loss of target species because of the grid. A possible cause might be clogging of the grid, which could be solved by increasing the grid area. Therefore, this study compared the size selectivity of by-catch species and target species in a double-trawl configuration in which one trawl was equipped with a standard grid (6.30 m^2), and the other trawl was equipped with a grid that had a 50% larger surface area (9.45 m^2). The results demonstrated that the size selectivity and catch efficiency of the target species were unaffected; neither was there any significant difference between the two grids in terms of wanted by-catch species [blue whiting (*Micromesistius poutassou*), horse mackerel (*Trachurus trachurus*), and greater argentine (*Argentina silus*)]. However, the larger grid caught significantly more unwanted by-catch species [haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), and hake (*Merluccius merluccius*)]. Approximately one-third of the accumulated catches comprised the target species, one-third of wanted by-catch species, and one-third of unwanted by-catch species, demonstrating the by-catch challenges in this fishery. Simultaneously, none of the by-catch limits were exceeded.

1. Introduction

The fishery for Norway pout has declined substantially over the past three decades, and the total allowable catch for the North Sea, Skagerrak, and Kattegat was set to 254 038 tons for 2021 (ICES, 2020). However, even though the quotas vary from year to year because of the short life span of this species and the fluctuating stock recruitment, annual landings are usually well below the annual quota (ICES, 2020). This small gadoid species is found throughout the North Sea, all around the UK, up to Iceland and along the Norwegian coast (Lambert et al., 2009). However, because this species has no schooling behavior and lives scattered close to the seabed, sufficient catch densities are only encountered in a few areas, mostly Fladen-ground and Egersund-ground along the Norwegian trench. It is in these areas that most of the fisheries targeting Norway pout are found. The fishery is conducted both in EU and Norwegian Exclusive Economic Zone (EEZ), with different management regulations, however, two countries Denmark and Norway account for 98% of the annual catches of Norway pout (Eigaard et al., 2021).

Given the scattered distribution of Norway pout, the trawls that are used in the fishery are commonly large opening trawls towed in a double-trawl configuration. In addition, because the species shows vertical diel migration, the vessels only fish during daylight when the species is closest to the seabed. In the Norwegian fishery the minimum legal mesh size in the codend is 16 mm, inevitably causing the fishery to have severe by-catch levels (ICES, 2017; Kvalsvik et al., 2006). Norway pout, which has no minimum landing size meaning that all sizes are targeted, is caught for reduction (i.e., extraction of fish oil and fish meal) (ICES, 2017; Eigaard et al., 2021). The fishery targeting Norway pout is a multispecies fishery with both wanted and unwanted by-catch species. All vessels that catch Norway pout also have quota for blue whiting (*Micromesistius poutassou*), which is targeted simultaneously. Nonquota

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species, such as Atlantic horse mackerel (*Trachurus trachurus*) and silvery pout (*Gadiculus argenteus*), are regarded as wanted by-catch species. Several vessels also have quota for Atlantic mackerel (*Scomber scombrus*), herring (*Clupea harengus*), and/or greater argentine (*Argentina silus*), which is allowed as by-catch up to given percentage and is drawn from the specific quota of each vessel (ICES, 2017). However, even though these can be regarded as wanted by-catch species, the vessels commonly prefer to target these species directly because this gives them a higher price when landed for human consumption. Species that are regarded as choke-species and, thus, as unwanted by-catch are haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), saithe (*Pollachius virens*), cod (*Gadus morhua*), hake (*Merluccius merluccius*), and monkfish (*Lophius piscatorius*), among others (ICES, 2017; Kvalsvik et al., 2006).

Current regulations limit the by-catch of cod, haddock, saithe, and whiting to a maximum of 20% (sum of those species by weight per haul), monkfish up to 0.5%, and herring and greater argentine up to 10% each (if the vessels have no quota for these species) (ICES, 2017). With long towing times of 8–10 h, and high catch rates up to 10 tons per hour, the amount of by-catch can be high. To reduce the fish by-catch, it has been mandatory since 2010 to apply a rigid sorting grid in the fishery, with a maximum bar spacing of 40 mm in the Norwegian EEZ and of 35 mm in the European EEZ (ICES, 2017). Although the introduction/implementation of the sorting grid has reduced the levels of by-catch of the largest fish, by-catch of juvenile fish species remains an issue (ICES, 2017; Eigaard et al., 2021). Therefore, it would be relevant to quantify the levels of nontarget species in the total catch.

Eigaard et al. (2012) reported that the grid, in addition to releasing by-catch species, also had a length-dependent release of the target species. This was confirmed nearly a decade later by another study by Eigaard et al. (2021), documenting a loss of target species with the sorting grid system. Previous studies on rigid sorting grids documented that the size-selective properties are affected by the catch density, with high entry rates having a negative impact on size selectivity (Sistiaga et al., 2010, 2016). High entry rates can cause blockage of the grid, subsequently reducing the probability of fish contacting the grid and attempting to escape (Sistiaga et al., 2016). In the Norway pout fishery, the entry rates vary between 1 and 10 tons per hour. This means that, with such high entry rates, the grid can be saturated, subsequently reducing its selective capacity.

A common method to aid the release of by-catch species is to increase the mesh size and/or change the mesh configuration in the codend. However, considering the small size of Norway pout this would cause an even larger loss in the target species, while by-catch species larger than Norway pout would still be retained. Also, changing the mesh size and/or configuration would not affect the issue of saturation of the grid during high entry rates. One possible solution to reduce the loss of target species is increasing the size of the grid and its surface area, which could mitigate the issue of lost target species. However, an increased retention of target species could also cause an increase in unwanted by-catch species and vice versa. Therefore, this study compared the traditional sorting grid used in the Norwegian fishery for Norway pout with that of

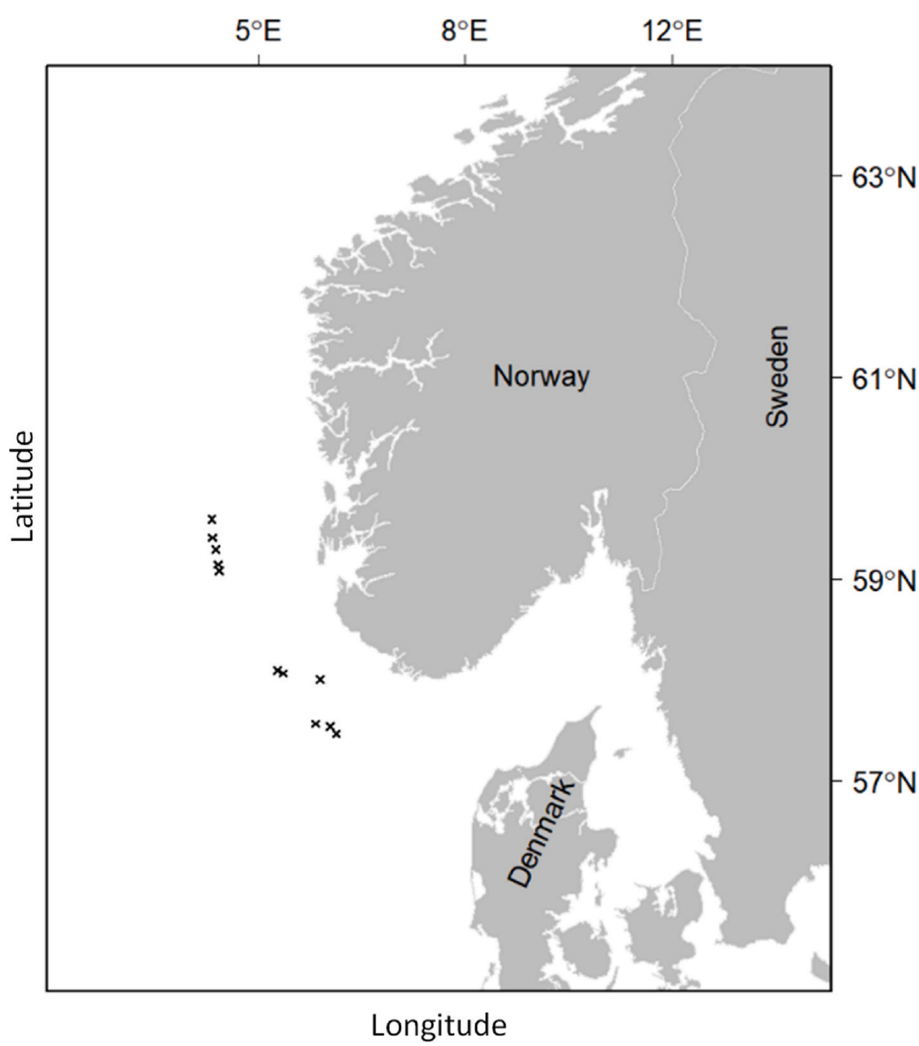

Fig. 1. Map showing the area in which the experimental trails were conducted (indicated by crosses).

an enlarged sorting grid. Specifically, the study investigated: (i) whether an enlarged sorting grid would reduce the loss of target species compared with the standard grid; (ii) whether an enlarged sorting grid would increase catches of by-catch species compared with the standard grid; and (iii) what the proportion of target and nontarget species would be in the catches caught with the standard grid and the large grid.

2. Materials and methods

2.1. Experimental trials

The cruise was conducted from 11th to September 18, 2021 onboard the 53 m-long commercial trawler *MTr Fiskebank*. The trails took place off the southwest coast of Norway (Fig. 1) on fishing grounds where Norway pout is commonly targeted.

Two identical Egersund Expo 1500 meshes trawl were used, with three 100 m-long bridles on each side. The lower bridle was equipped with a 20 cm disc in the center to avoid excessive abrasion of the sweeps. The sweeps were 30 m long followed by 25 m-long connector ropes, which were attached to the otter boards. The otter boards (Thyborøn type 22 pelagic doors) weighed 3000 kg, and were 11 m^2 each. The clump in the middle weighed 5500 kg. The Expo trawls had a fishing line of 67.4 m and a headline of 66.1 m. The fishing line was equipped with a 13 m-long rock hopper gear (Ø 10″) in the center followed by 27.2 m-long chains on each side. The starboard trawl was equipped with a sorting grid according to the regulations. The grid had a width of 180 cm, was 350 cm long (6.30 m^2), and had a bar spacing of 39.42 mm ± 1.79 mm (mean ± SD). The port trawl was equipped with the experimental grid, which had a width of 270 cm, a length of 350 cm (9.45 m^2), and a bar spacing of 40.55 mm ± 0.93 mm (mean ± SD). Both grids comprised five sections that where 70 cm long, ensuring that the grid could be stored on the net drums. The grids were mounted at a 45° into four panel sections. The escape outlet was in front of the grid in the lower panel. To avoid the unwanted loss of target species, both grids had a small guiding panel in front of the escape opening in addition to bungee cords that kept the escape opening close to the grid (Fig. 2). The codends that followed the grids were both 51 m long and had a circumference of 40 m. The codend that followed the large experimental grid had a mesh size of 19.00 ± 0.65 mm (mean ± SD), whereas the codend that followed the standard grid had a mesh size of 19.23 ± 0.74 mm (mean ± SD). The trawl geometry and performance were continuously monitored using Scanmar sensors measuring the distance between the otter boards, trawl height, and catch volume. The towing speed was between 3.0 and 3.5 knots.

2.2. Data collection

After each tow, the catch in the codend from the two trawls was pumped onboard into separate refrigerated-sea-water tanks (RSW). In total, 12 baskets of fish were sampled from each codend. To ensure a representative sample, four baskets were filled at the beginning, four in the middle, and four at the end of the onboard pumping of the catch. This resulted in ~300–350 kg of fish from each codend. Directly after pumping, the factory chief inspected each tank and estimated the catch

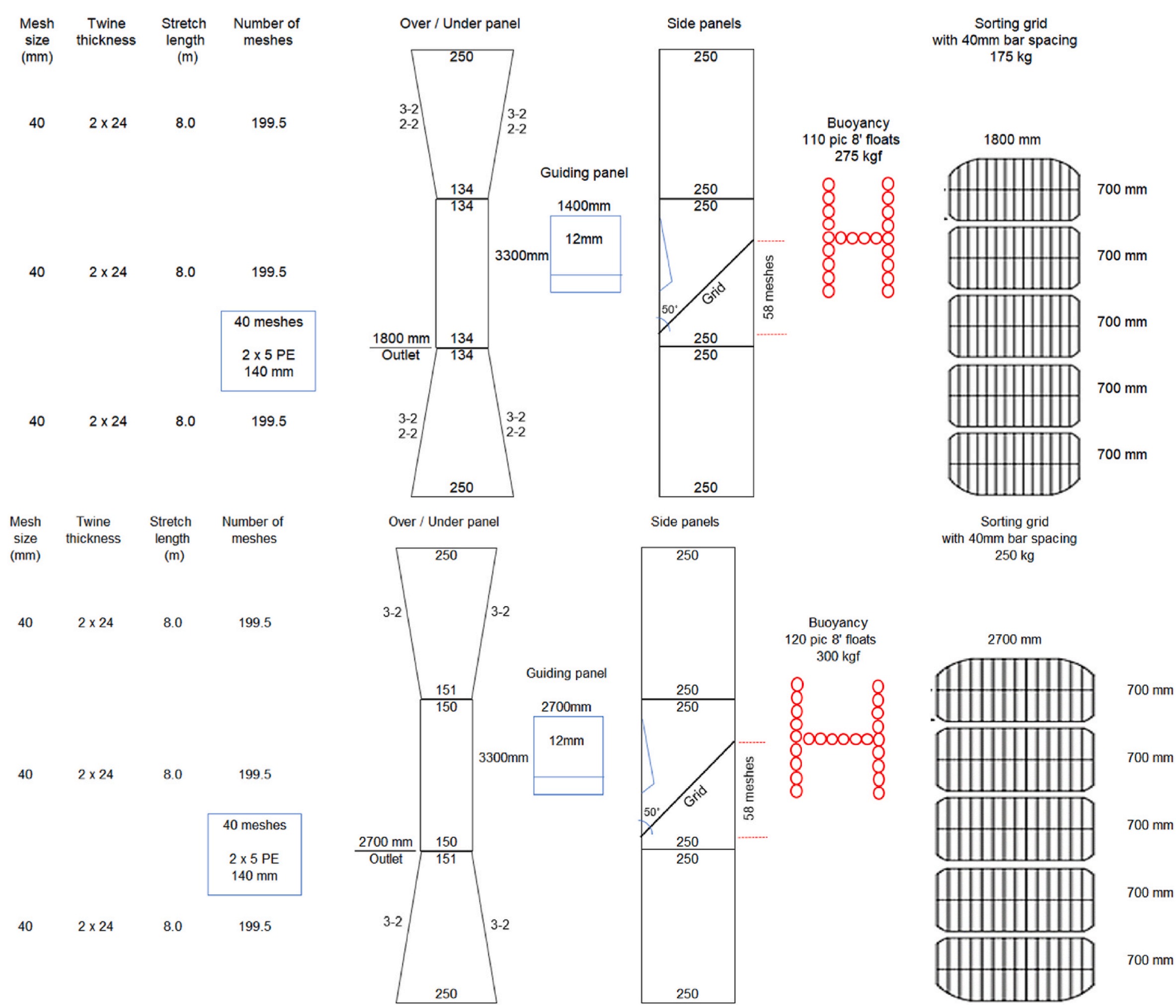

Fig. 2. Schematics of the grid sections. **Upper:** Specifications of the standard 1.8 m-wide grid. **Lower:** Specifications of the experimental 2.7 m-wide grid.

volume for each codend. The samples were sorted according to species. The weight was registered for each species and, if possible, the length of all fish was measured to the lowest centimeter. Subsamples of 10–20 kg were taken of Norway pout and blue whiting and the total weight and the subsample weight recorded. The subsampling factors were calculated by multiplying the subsample factor based on the weight from the fish measured divided by the total sample weight and the sample weight divided by the total catch weight (Table 1).

2.3. Modeling the size-dependent catch efficiency

The catch data were analyzed by modeling the size-dependent catch efficiency (Herrmann et al., 2017) using the statistical software SELNET (Herrmann et al., 2016). This method models the length-dependent catch comparison rate (CC_l) summed over hauls using Equation (1):

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j} + \frac{nc_{lj}}{qc_j}\right\}} \tag{1}$$

where nc_{lj} and nt_{lj} are the numbers of fish of each species that were measured in each length class l for the standard grid (control) and large grid (treatment) trawls in haul j. qc_j and qt_j are sampling factors quantifying the fraction, based on weight, of the catch in the codends being length-measured in the respective hauls. m is the number of hauls in which sufficient numbers of each species were caught to be included in the analysis. The functional form for the catch comparison rate $CC(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing Equation (2):

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j} \times ln(CC(l,\boldsymbol{v})) + \frac{nc_{lj}}{qc_j} \times ln(1.0 - CC(l,\ \boldsymbol{v}))\right\}\right\} \tag{2}$$

where $\boldsymbol{v}$ is a vector of the parameters describing the catch comparison curve defined by $CC\ (l,\boldsymbol{v})$. The outer summation in Equation (2) is the summation over length classes l. When the catch efficiency of the standard grid and that of the large grid trawl are similar, the expected value for the summed catch comparison rate would be 0.5 (baseline). Therefore, this baseline can be applied to judge whether there is a difference in catch efficiency between the two trawls. The experimental CC_l was modeled by the function $CC(l,\boldsymbol{v})$ using Equation (3):

$$CC(l,\ \boldsymbol{v}) = \frac{exp(f(l,\ v_0, ..., v_k))}{1 + exp(f(l,\ v_0, ..., v_k))} \tag{3}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ were estimated by minimizing Equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models also considered as potential models for the catch comparison $CC(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multimodel inference to obtain a combined model (Burnham and Anderson 2002). The ability of the combined model to describe the experimental data was evaluated based on the p-value. The p-value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases in which the data are subject to overdispersion (Wileman, 1996). Based on the estimated catch comparison function $CC(l,\boldsymbol{v})$, we obtained the relative catch efficiency (also named catch ratio) $CR(l,\boldsymbol{v})$ between the two trawls using Equation (4):

$$CR(l,\ \boldsymbol{v}) = \frac{CC(l,\ \boldsymbol{v})}{(1 - CC(l,\ \boldsymbol{v}))} \tag{4}$$

$CR(l,\boldsymbol{v})$ represents the relationship between catch efficiency of the large grid and standard grid trawl. If the catch efficiency of both trawls is

Table 1
Overview of each haul showing date, time of deployment, towing time, catch weight, and subsampling factor for the standard grid (SG) and the large grid (LG).

	Haul nr	1	2	3	4	5	6	7	8	9	10	11	12
	Date	11.09.2021	11.09.2021	12.09.2021	13.09.2021	13.09.2021	14.09.2021	14.09.2021	15.09.2021	16.09.2021	16.09.2021	17.09.2021	17.09.2021
	Time (UTC)	09:22	20:25	07:20	04:33	13:17	04:12	12:40	03:29	02:48	14:25	04:23	13:00
	Depth (m)	157	149	155	153	173	168	175	161	198	165	138	–
	Towing time (hh:mm)	8 h 15 min	8 h 12 min	10h 35 min	6 h 23 min	5 h 2 min	6 h 55 min	5 h 58 min	5 h	8 h 56 min	5 h 35 min	6 h 55 min	4 h 50 min
	Catch weight SG (kg)	32000	7000	42000	21000	17000	22000	12000	18000	13000	9000	10000	10000
	Catch weight LG (kg)	30000	8000	53000	22000	18000	18000	8000	19000	12000	8000	8000	10000
Sub-sampling factor	**Norway pout (SG)**	0.0013	0.0030	0.0015	0.0020	0.0024	0.0012	0.0016	0.0025	0.0041	0.0026	0.0020	0.0040
	Norway pout (LG)	0.0007	0.0040	0.0007	0.0011	0.0032	0.0016	0.0021	0.0024	0.0094	0.0031	0.0032	0.0026
	Blue whiting (SG)	0.0018	0.0471	0.0044	0.0047	0.0084	0.0116	0.0101	0.0063	0.0022	0.006	0.0314	0.0034
	Blue whiting (LG)	0.0023	0.0392	0.0069	0.0049	0.0087	0.0168	0.0141	0.0048	0.0022	0.0085	0.0191	0.0042
	Horse mackerel (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0116	0.0247	0.0187	0.0239	0.0366	0.0314	0.0325
	Horse mackerel (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	0.0263	0.0427	0.0411	0.0295
	Mackerel (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0116	0.0247	0.0187	0.0239	–	0.0314	0.0325
	Mackerel (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	–	–	0.0411	0.0295
	Argentine (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0166	0.0247	0.0187	0.0239	0.0366	0.0314	0.0325
	Argentine (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	0.0263	0.0427	0.0411	0.0295
	Haddock (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0166	0.0247	0.0187	0.0239	0.0366	0.0314	0.0325
	Haddock (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	0.0263	0.0427	0.0411	0.0295
	Hake (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0166	0.0247	0.0187	0.0239	0.0366	–	0.0325
	Hake (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	0.0263	0.0427	0.0411	0.0295
	Whiting (SG)	0.0111	0.0471	0.0078	0.0171	0.0187	0.0166	0.0247	0.0187	–	0.0366	0.0314	0.0325
	Whiting (LG)	0.0121	0.0392	0.0069	0.0151	0.0177	0.0168	0.0382	0.0181	–	0.0427	0.0411	0.0295

equal, then $CR(l,\mathbf{v}) = 1.0$. $CR(l,\mathbf{v}) = 1.5$ would mean that the large grid trawl is catching 50% more of the species with length l than the standard grid trawl. By contrast, a $CR(l,\mathbf{v})$ of 0.8 would mean that the large grid trawl is only catching 80% of the species with length l caught by the standard grid trawl.

To provide significant differences in catch efficiency between the trawls, we estimated confidence intervals (CIs) for $CC(l,\mathbf{v})$ and $CR(l,\mathbf{v})$ using a double bootstrapping method (Herrmann et al., 2017). This double bootstrapping method accounts for between-haul variability (the uncertainty in the estimation resulting from between-haul variation of catch efficiency in the trawls) as well as within-haul variability (the uncertainty about the size structure of the catch for the individual hauls, including the effect of subsampling). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between-haul variation was performed paired for the large grid and standard grid trawl, taking full advantage of the experimental design with the trawls being fished in a twin-trawl setup (in parallel). By multimodel inference in each bootstrap iteration, the method also accounted for the uncertainty resulting from uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron 1982) confidence intervals. To identify sizes of species with significant differences in catch efficiency, we checked for length classes in which the 95% CIs for the catch ratio curve did not include 1.0. Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using Equation (5):

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_j} \right\}} \tag{5}$$

where the outer summation $\sum_l$ covers the length classes in the catch during the experimental fishing period.

2.4. Species dominance

Catch dominance curves are often used to quantify information about the pattern of relative species abundances for a given sample. Here, we use catch dominance curves based on weight to quantify the dominance of the individual species in the catch. Generally, dominance curves are based on ranking of species in a sample in decreasing order of their abundance (Clarke, 1990). This implies that the species ranking could vary among stations, making it difficult to compare dominance curves among different gears. Therefore, we kept the species ranking fixed according to the species ID (Table 1).

We then estimated the catch dominance curve for each net configuration using Equation (6) (Warwick et al., 2008):

$$d_{ij} = \frac{q_{ij} \times n_{ij} \times w_{ij}}{\sum_{i=1}^{K} \{ q_{ij} \times n_{ij} \times w_{ij} \}} \tag{6}$$

where j represents the haul and i is the species index (species rank) that was predefined. n_{ij} is the number of individuals of the species i being counted in the subsample in haul j. w_{ij} is the weight of the counted subsample of species i in haul j, whereas q_{ij} is the fraction of species i in the catch being counted in haul j. K is the total number of species considered.

To better represent species dominance patterns, we also estimated the cumulative dominance curves using Equation (7):

$$D_{Ij} = \frac{\sum_{i=1}^{I} \{ q_{ij} \times n_{ij} \times w_{ij} \}}{\sum_{i=1}^{K} \{ q_{ij} \times n_{ij} \times w_{ij} \}} \text{ with } 1 \leq I \leq K \tag{7}$$

where I is the species index summed up to in the nominator.

The 95% CIs for the dominance patterns were estimated by using Equations (6) and (7) inside each of the bootstrap iterations applied to estimate the uncertainties for the catch comparison and catch ratio curves.

3. Results

Twelve valid hauls were conducted during the cruise. The towing time varied between 4 and 10 h, with catch weights ranging from 8 to 53 tons per codend (Table 1). The towing speed was between 3.0 and 3.5 knots. The subsampling factors are presented in Table 1, whereas the number of fish measured and the total number of fish caught are presented in Table 2.

For all species, the estimated p-value was <0.05 (Table 2). However, the modeled catch comparison curve followed the main trend in the experimental data for all species (Fig. 3). Therefore, it was assumed that the low p-values obtained were a consequence of overdispersion in the experimental data that resulted from working with pooled and subsampled data with low sampling rates (Table 1). Such cases have previously led to low p-values and high dispersion (Brčić et al., 2015; Alzorriz et al., 2016; Notti et al., 2016).

The size distribution curves for Norway pout (Fig. 2) show that the trawls with the two different grids caught nearly identical length classes. Furthermore, the catch comparison and catch ratio curves for Norway pout with the 95% CIs overlap the dashed horizontal line, which means that the two grids fished equally and that there was no significant difference in catch efficiency between them (Fig. 3).

Blue whiting, horse mackerel, and greater argentine are all wanted by-catch species. The size distribution curves show that the two grids had similar catch patterns, except for blue whiting, which the standard grid caught more of the smallest length classes (Fig. 4). The catch comparison curves and the catch ratio curves did not show any significant differences in the catch efficiency for these three species (Fig. 4).

Haddock, whiting, hake, and mackerel are all regarded as unwanted by-catch species. The large grid caught significant more individuals of all those species, except mackerel (Fig. 5). The catch ratio and catch comparison curves show that the large grid caught significantly more whiting between 5.6 and 28.5 cm and 39.5 and 50.5 cm in length, and hake between 33.5 and 41.5 cm (Fig. 5). In addition, the large grid caught significantly more haddock, even though the significance was less than for the two other species and for fewer length classes (between 20.5 and 26.5 cm of length) (Fig. 5).

Fig. 6 shows the accumulated catch contribution for each species caught summarized for all hauls. It includes all species presented in Figs. 3–5 and in addition herring, which was not caught in large enough numbers to conduct a length-dependent analysis. Catches with the standard grid contained nearly equal amounts of target species (Norway pout), wanted by-catch species (blue whiting, horse mackerel, and greater argentine), and unwanted by-catch species (haddock, whiting, hake, herring, and mackerel) compared with the catches caught in the trawl with the large grid (Fig. 6, Table 3). However, when looking at the percentages caught of each species, mackerel constituted most of the unwanted by-catch species, 24.63% (CI: 9.77–38.07) for the standard grid and 23.59% (CI: 8.54–43.82) for the large grid (Table 4). Of the gadoid species, haddock was caught most, but only constituted 4.64% (CI: 2.09–8.79) with the standard grid and 5.62% (CI: 2.63–11.12) with the large grid of the total catch (Table 4).

4. Discussion

Decades of research on selectivity in trawls has led to significant reductions in unwanted by-catch species and sizes in many fisheries (Kennelly and Broadhurst, 2021). However, in several trawl fisheries targeting small-sized species, unwanted by-catch of juveniles, which often are of the same size as the target species, is a persisting issue (Larsen et al., 2018; Eigaard et al., 2021). The fishery for Norway pout is one such fishery (Eigaard et al., 2012). With a minimum mesh size of 16 mm in the codend and a mandatory sorting grid with 40 mm-bar spacing, the catches can still contain large quantities of by-catch. Even

Table 2
Fit statistics showing the *p*-value, deviance, degrees of freedom (DOF), and number of fish length measured as well as the total number of fish caught for each species in the standard grid and the large grid.

Species	*P*-value	Deviance	DOF	Fish measured		Total number of fish	
				Standard grid	Large grid	Standard grid	Large grid
Norway pout	<0.0000	76.22	8	5334	5091	2 725 407	2 818 006
Blue whiting	<0.0000	291.99	26	3676	3747	846 544	733 258
Horse mackerel	0.0029	21.68	7	1663	1687	93 918	95 467
Argentine	0.0244	21.99	11	934	989	37 716	39 657
Haddock	<0.0000	103.87	24	1153	1380	41 198	58 928
Whiting	<0.0000	118.9	19	144	244	7 502	13 035
Hake	<0.0000	56.78	10	19	50	1 104	5 312
Mackerel	0.0001	40.62	13	1950	1806	176 334	191 257

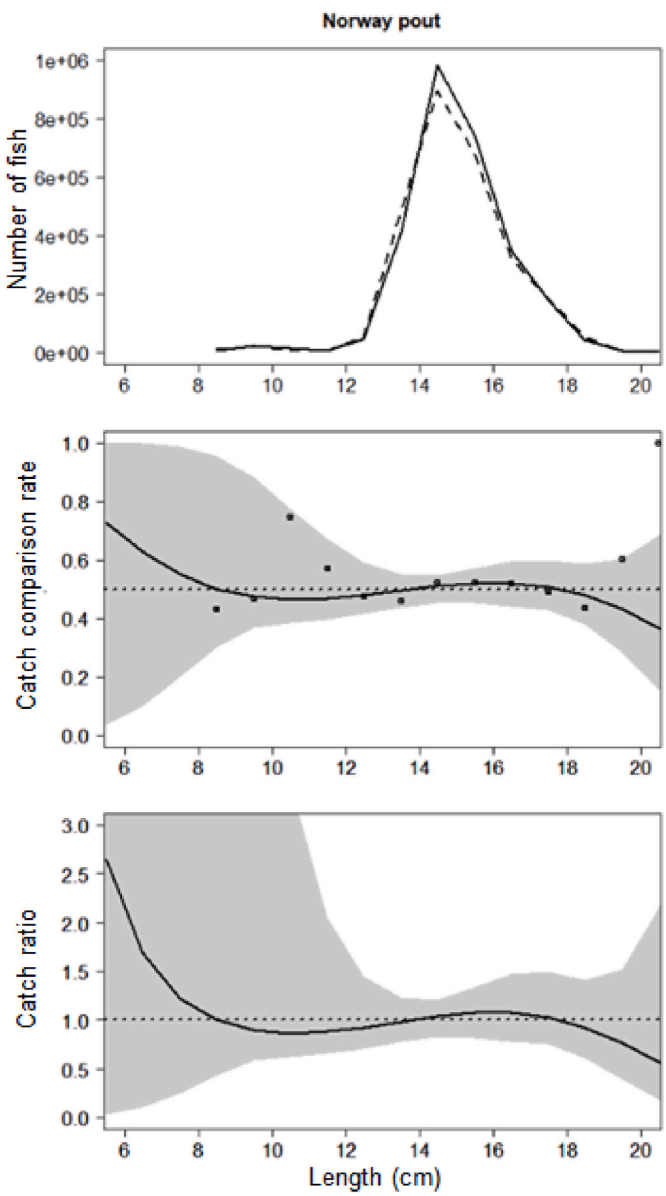

Fig. 3. Upper: Size distribution of Norway pout caught in the trawl with the large grid (solid line), and standard grid (dashed line). **Middle**: Catch comparison rate. **Lower**: Catch ratio curve. The black dots denote the experimental data point, and the gray areas denote the 95% confidence intervals. The dashed horizontal lines represent the level where the two designs caught equally.

though the introduction of the sorting grid in both the Norwegian and EU fishery has significantly reduced the catches of large gadoids, small gadoids and other unwanted by-catch species can still be a caught in large quantities (Eigaard et al., 2012; ICES, 2017). Given that the catches may contain a maximum of 20% haddock, cod whiting, or hake, 10% herring, and 0.5% monkfish, large quantities of by-catch can be a problem and can be regarded as choke species.

In addition, multiple studies have reported the loss of target species when applying grids (Eigaard and Holst 2004; Eigaard et al., 2012, 2021). Given that the catch rates per towing hour can be high, a possible cause of the loss of target species could be saturation and clogging of the grid, as experienced in other fisheries (Sistiaga et al., 2016). Therefore, a possible solution could be to increase the surface area of the grid. However, as the current study demonstrates, increasing the surface area of the grid with 50% had no significant effect on the size selectivity of Norway pout or on the wanted by-catch species (blue whiting, horse mackerel, and greater argentine). However, the larger grid caught significantly more of the unwanted by-catch species (haddock, whiting, and hake). Of the unwanted by-catch species, only the catch efficiency of mackerel was not significantly different between the two grids. A possible explanation for this increased retention of these gadoids species could be the increased surface area of the grid, which increases the probability of fish contacting the grid and, therefore, being retained (Sistiaga et al., 2010, 2016; Larsen et al., 2019).

A possible option to reduce the retention of unwanted by-catch species in reducing the bar spacing in the grid. The bar spacing (40 mm in Norwegian EEZ and 35 mm in EU EEZ) allows the passage of relatively large fish compared with the size of Norway pout. Reducing the bar spacing would likely reduce the by-catch more than would increasing the surface area of the grid; however, this could also negatively impact the retention of the target species as well as wanted by-catch species. The reduction of by-catch species and the loss of target species as a consequence of reducing the bar spacing in the Norway pout fishery have both been documented previously. Eigaard and Holst (2004) tested a grid with 24 mm bar spacing in combination with a square mesh panel and reported a reduction not only in haddock (37%) and (57%), but also in target species (7%). Although significant by-catch reduction was achieved in the current study, it was not possible to determine whether the 22 mm grid or the square mesh panel was responsible for the reduction of the by-catch species. Kvalsvik et al. (2006) tested three different bar spacings, 19 mm, 22 mm, and 25 mm. They reported 94.6% and 62.4% reductions in gadoids in two different trials, although the loss of target species (Norway pout and blue whiting) was 32.8% and 22%, respectively (Kvalsvik et al., 2006). In general, the smaller the bar spacing, the larger the reduction in not only unwanted by-catch species, but also target species. Other possible solutions to reduce the by-catch of unwanted species is improved information during fishing. This can possibly be achieved using cameras monitoring the fish entering the trawl (Rosen et al., 2013), or using near-real time maps showing the abundance of the target and by-catch species (Reid et al., 2019). The latter would enable the skipper to trawl in areas where the abundance of the target species is high, while the abundancy of by-catch

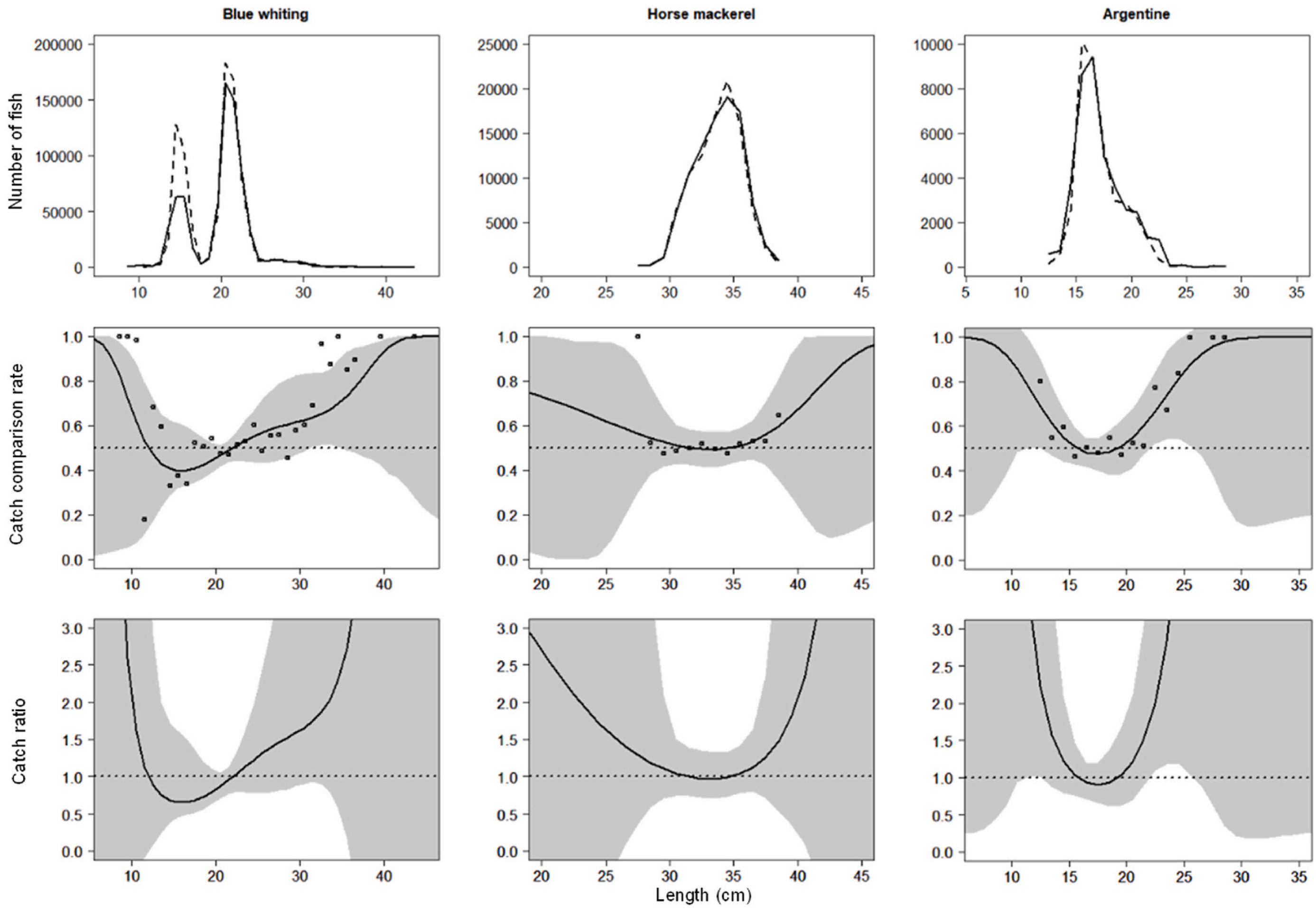

Fig. 4. Upper: Size distribution of wanted by-catch species caught in the trawl with the large grid (solid line), and standard grid (dashed line). **Middle**: Catch comparison rate. **Lower**: Catch ratio curve. The black dots denote the experimental data point, and the gray areas denote the 95% confidence intervals. The dashed horizontal lines represent the level where the two designs caught equally.

species is low, and in this way improve the catch efficiency of the target species, reducing the catches of by-catch species, with a positive side effect of also reducing the time trawled, and thus reducing seabed impact, and fuel consumption.

As this study demonstrates, only approximately one-third (ca. 33%) of the catch constituted of the target species, whereas the remaining two-thirds contained wanted (ca. 33%) and unwanted (ca. 33%) by-catch species (Fig. 6, Table 3). Even though Norway pout is the target species, most of the vessels have quotas for other species, such as blue whiting and greater argentine, which can be caught simultaneously. Horse mackerel is a nonquota species and, therefore, also a wanted by-catch species. Other species, such as cod, haddock, whiting, and hake, are strictly regulated with maximum by-catch limits (as outlined above) and, therefore, are regarded as choke species (ICES, 2017). In the current study, a major part of the unwanted by-catch was mackerel, and gadoids and herring only constituted a minor part of the total catch (Table 4). Therefore, none of the by-catch limits according to the legislation were violated. Mackerel is an unwanted by-catch species in this stance because, even though many vessels have a quota for mackerel, the vessels aim to target mackerel separately because the price is much higher when delivered for human consumption. Nevertheless, in many cases, the by-catch of unwanted species, especially gadoids, can be significant and has negative consequences for the spawning stock biomass (Eigaard and Holst, 2004). This confirms the need to seek additional solutions that will significantly reduce the retention of unwanted by-catch species in this fishery.

Multiple studies have tested and demonstrated various types of sorting grid in the Norway pout fishery, including the use of different materials, inclination angles, orientations, and bar spacings (Eigaard and Holst 2004; Kvalsvik et al., 2006; Eigaard et al., 2012; ICES, 2017). Common for all these studies, including the current study, is that the reduction in by-catch is significant but not sufficient, or the loss of target species is too high. Achieving optimal selectivity in this fishery by applying large grids is difficult, if not impossible. The even larger grid tested in this study only resulted in increased retention of gadoids. The reason for this increase is unclear, and we don't know whether it's caused by behavioral, morphological, a possible change in water flow. Eigaard et al. (2021) tested a system termed 'Excluder' in comparison with a grid with 35 mm bar spacing in the Norway pout fishery. The excluder, which is a netting-based 30 m-long 'tube' inside the trawl with a 70 mm mesh size, reduced the retention of herring to (21%), whiting (6%), mackerel (5%), American plaice (*Hippoglossoides platessoides*) (70%), witch flounder (Glyptocephalus cynoglossus) (15%), and lesser silver smelt (Argentina sphyraena) (71%), and increased the retention of Norway pout by 32%, compared to the standard grid (Eigaard et al., 2021). The increased retention of target species was possibly because the sorting area was 15 times larger than the standard grid (Eigaard et al., 2021). These promising results should be further tested, possibly reducing the mesh size even more to reduce the retention of unwanted by-catch species.

Declaration of competing interest

The authors declare that they have no known competing financial

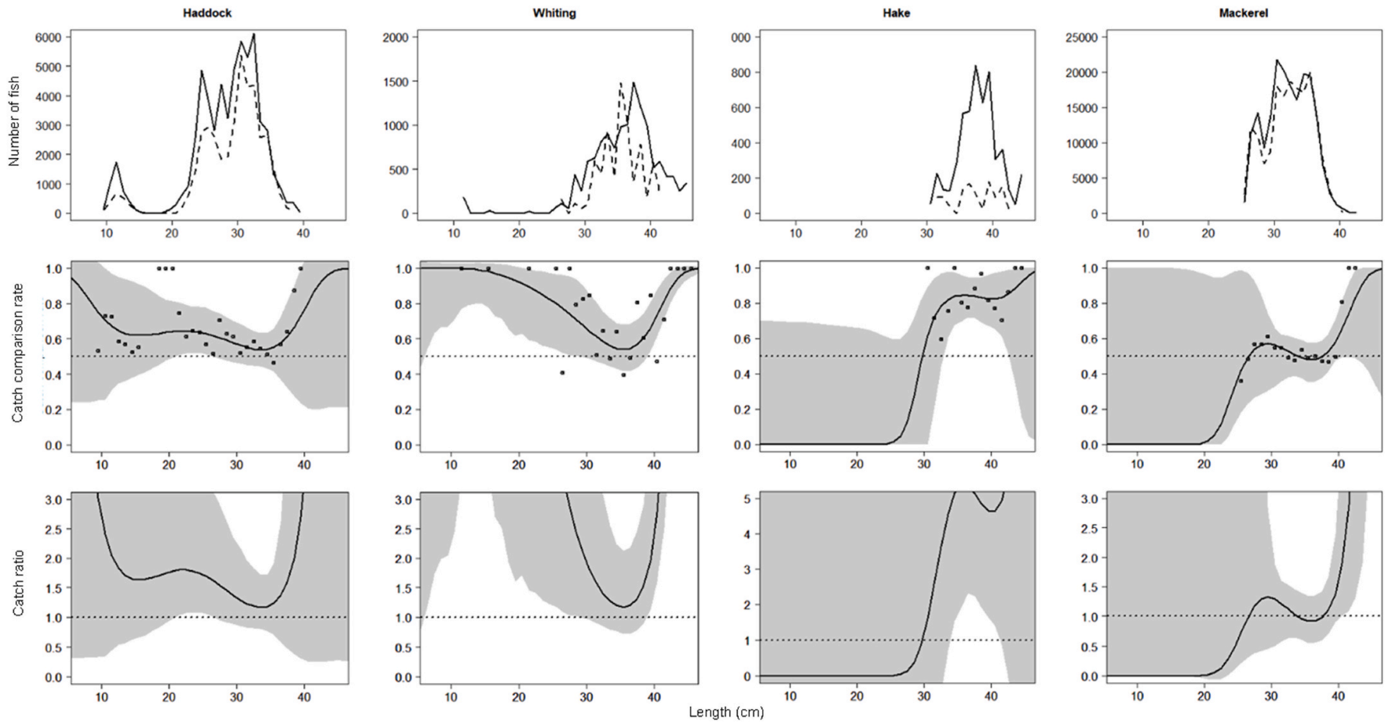

Fig. 5. **Upper**: Size distribution of wanted by-catch species caught in the trawl with the large grid (solid line), and standard grid (dashed line). **Middle**: Catch comparison rate. **Lower**: Catch ratio curve. The black dots denote the experimental data point, and the gray areas denote the 95% confidence intervals. The dashed horizontal lines represent the level where the two designs caught equally.

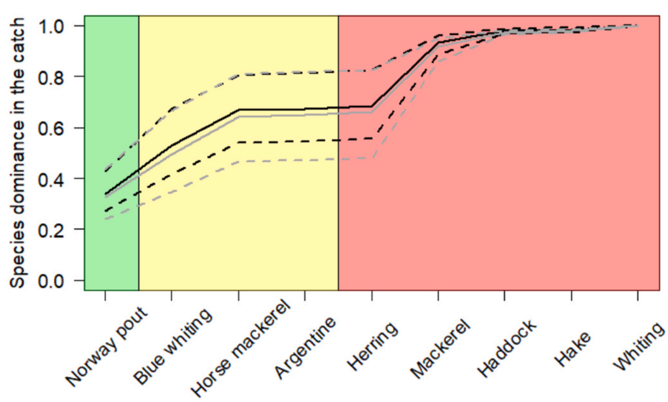

Fig. 6. Species dominance in the catch. The curves (solid lines) with 95% confidence intervals (dotted lines) represent the cumulative species dominance for the catches caught with the standard (black), and the large grid (gray). The green, yellow, and red areas represent the target species, wanted by-catch species, and unwanted by-catch species. respectively.

Table 3
Catch composition, based on all hauls, divided into target species (Norway pout), wanted by-catch species (blue whiting, horse mackerel, and greater argentine), and unwanted by-catch species (haddock, whiting, hake, herring and mackerel) (95% confidence intervals in brackets).

	Target species	Wanted by-catch species	Unwanted by-catch species
Standard grid	34.0 (27.4–42.8)	34.6 (28.2–39.6)	31.4 (44.5–17.6)
Large grid	32.3 (24.1–43.7)	33.3 (23.8–38.9)	33.9 (52.1–17.4)

Table 4
Catch percentage for each for the species caught summed for all hauls (95% confidence intervals in brackets).

Species	Standard grid	Large grid
Norway pout	33.99 (27.37–42.28)	32.74 (24.09–43.71)
Blue whiting	19.00 (10.16–31.11)	16.75 (8.11–27.14)
Horse mackerel	13.78 (8.39–21.09)	14.85 (8.48–23.42)
Argentine	0.55 (0.35–0.86)	0.58 (0.37–0.98)
Herring	1.32 (0.42–2.90)	1.16 (0.43–2.36)
Mackerel	24.63 (9.77–38.07)	23.59 (8.54–43.82)
Haddock	4.64 (2.09–8.79)	5.62 (2.63–11.12)
Hake	0.40 (0.19–0.62)	0.66 (0.35–1.05)
Whiting	1.68 (0.89–2.65)	2.05 (1.40–2.75)

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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