Aquat. Living Resour. 22, 1–10 (2009)

DOI: 10.1051/alr/2009001
www.alr-journal.org

Aquatic
Living
Resources

A comparison of bycatch and discard mortality in three types of dredge used in the Portuguese *Spisula solida* (solid surf clam) fishery

Francisco Leitão[a], Miguel B. Gaspar, Miguel N. Santos and Carlos C. Monteiro

Instituto Nacional de Recursos Biológicos (INRB, IP) /IPIMAR, Avenida 5 de Outubro s/n, 8700-305 Olhão, Portugal

Received 3 October 2008; Accepted 17 November 2008

Abstract – Despite the importance of the dredge fishery in Portugal, few studies have focused on bycatch and discard mortality. Catches from three types of dredge: north dredge (ND); grid dredge (GD); and traditional dredge (TD), currently used in the *Spisula solida* (Bivalvia: Mactridae) fishery, were compared in order to characterize bycatch and to estimate discard mortality. In TD and ND, the catch was retained in a net bag, whereas in the GD a metallic grid cage was used. Tows were carried out on sandy bottoms at depths ranging from 5 to 10 m. Bycatch differed significantly between dredges. The ratio of bycatch abundance to *S. solida* was 0.22:1 for ND, 0.10:1 for GD and 0.33:1 for TD. The weight ratio was 0.15:1, 0.14:1 and 0.32:1 for ND, GD and TD, respectively. Although a lower bycatch was observed for GD, higher mortality (ND: 10%; TD: 20%; GD: 36%) was estimated for this dredge. However, taking into consideration the fishing yields obtained for each dredge combined with the fact that this fishery is managed by daily quota per vessel, our results showed that, at daily quota level, discard mortality was lower when GD was used. Our study suggests that in output-controlled fisheries, there are obvious advantages in developing dredges with rigid retention structures, such as metallic grids, because these are more selective and efficient than dredges that use net bags. At species level, the bycatch mortality to attain quota varied among dredges. A "selective" and persisting significant removal of bycatch species from biota may change benthic community structure. Therefore, clam fisheries should apply exploitation strategies that are goal-oriented and adaptive to the evolution of the macrofauna communities, which might include the use of different dredge types, thereby diversifying the bycatch and consequently avoiding the cumulative removal of specific macrofauna taxa.

Key words: Bycatch / Clam dredging / Discard mortality / Mollusc / Bivalve / *Spisula solida* / Atlantic Ocean

Résumé – Comparaison de la mortalité des captures accessoires et des rejets de trois types de drague à coquillages utilisés par la pêche portugaise de *Spisula solida*. Malgré l'importance de la pêche aux coquillages par draguage au Portugal, peu d'études sont focalisées sur la mortalité des captures accessoires et celle des rejets. Les captures effectuées par trois types of drague : la drague du nord (ND) ; la drague à grille (GD) ; et la drague traditionnelle (TD), couramment utilisées dans la pêche aux spisules ou venus/patagos, *Spisula solida* (Bivalves : Mactridés) sont comparées en vue de caractériser la mortalité de leurs captures accessoires et rejets. Pour les dragues TD et ND, les prises sont retenues dans un filet, tandis que GD est composée d'une grille métallique. Les coups de drague sont effectués sur des fonds sablonneux de 5 à 10 m de profondeur. Les captures accessoires diffèrent significativement entre dragues. La proportion de l'abondance des captures accessoires de *S. solida* est de 0,22:1 pour ND, 0,10:1, pour GD et 0,33:1 pour TD. La proportion en poids est respectivement 0,15:1, 0,14:1 et 0,32:1 pour ND, GD et TD. Bien que de plus faibles captures accessoires soient observées pour GD, des mortalités plus élevées sont estimées pour ce type de drague (ND : 10 % ; TD : 20 % ; GD : 36 %). Cependant, en tenant compte que les rendements de pêche obtenus pour chacune des dragues, combinés au fait que cette pêche est gérée par des quota journaliers et par bateau, nos résultats montrent que la mortalité est inférieure lorsque GD est utilisée. Notre étude, au niveau de la gestion des captures, montre qu'il y a des avantages évidents à développer les dragues avec des structures de rétention rigides, telles que des grilles métalliques parce qu'elles sont plus sélectives et plus efficaces que celles en filets. Au niveau des espèces, la mortalité des captures accessoires pour atteindre le quota de pêche varie avec le type de drague. Un retrait sélectif et persistant des espèces accessoires du milieu peut modifier

---

[a] Corresponding author: `fleitao@cripsul.ipimar.pt`

la structure de la communauté benthique. Ainsi, la pêche aux coquillages devrait appliquer des stratégies d'exploitation qui seraient orientées et adaptées à l'évolution des communautés de la macrofaune, ce qui peut inclure l'usage de différentes dragues, diversifiant les captures accessoires, et évitant les retraits cumulés de taxons spécifiques de la macrofaune.

1 Introduction

Maintaining marine biodiversity is an important priority for conservation. Fishing is one of the activities that most impacts marine communities, by removing rare and abundant species (with or without commercial interest), changing species composition and modifying or even destroying habitats (e.g. Hall 1999). Therefore, the catches of non-target species (termed bycatch), has become a major concern in the last two decades. The amount of bycatch in a given fishery largely depends on the methods and gears employed (Borges et al. 2001; Erzini et al. 2002; Gonçalves et al. 2007, 2008a,b). However, the impact of fisheries on bycatch species is not well known. Research has focused mainly on species of commercial or recreational importance and few studies have evaluated the impact on bycatch species (Philippart 1998). High mortality rates imposed on target and non-target species may alter species assemblages, which can also cross trophic levels and affect predator/prey relationships (Pauly and Christensen 2002). Discarding large amounts of bycatch species can lead in the long-term to changes in the structure of marine ecosystems (De Groot 1984; Dayton et al. 1995; Pauly and Christensen 2002; Harrington et al. 2005; Kelleher 2005). According to Pauly and Christensen (2002), a gradual transition in landings from long-lived, high trophic level, piscivorous bottom fish to short-lived, low trophic level invertebrates and planktivorous pelagic fish has been recorded over the last 30 years in many fisheries around the world. Moreover, the mortality of juveniles and subadults of important commercial and recreational species is thought to reduce recruitment, biomass and stocks, thus affecting other fisheries (Broadhurst 2000).

Increasing awareness of the amount of bycatch and its potential impacts on marine resources has led to the implementation of several technical measures, such as minimum mesh sizes, time/area restrictions and bycatch limits. Efforts have been made to modify fishing gears through the development of new gear designs and/or by introducing bycatch reduction devices in order to enhance selectivity and reduce bycatch and discards (Roosenburg and Jason 1999; Morgan and Chuenpagdee 2003; Valdemarsen and Suuronen 2003). However, most of these studies are related to trawls (Gaspar and Chícharo 2007). Concerning dredges and hydraulic dredges, some studies have examined the selectivity and/or efficiency of the gears (e.g. Caddy 1968; Nashimoto 1984; Chapman et al. 1977; McLoughlin et al. 1991; Dare et al. 1993; Gaspar et al. 1999, 2003b; Rambaldi et al. 2001; Campbell and Courtney 2006; Hauton et al. 2007), other with the fate of discarded juveniles of the target species (e.g. Gaspar and Monteiro 1999; Jenkins and Brand 2001; Maguire et al. 2002; Jenkins et al. 2004) and a few reported the impact of fisheries on bycatch species (e.g. Veale et al. 2001; Gaspar et al. 2001; Garcia et al. 2006).

Clam dredges are extensively used along the Portuguese coast. The commercial dredge fleet comprises 92 vessels (overall length: 4–14 m; engine power: 17–150 hp; crew: 1–5 fishers) that direct the fishing effort towards five species: the solid surf clam *Spisula solida*, the wedge clam *Donax trunculus*, the stripped venus *Chamelea gallina*, the smooth clam *Callista chione* and the razor clam *Ensis siliqua*. The relatively high value of commercial species (ranging between 2 and 10 euros per kg for first sale), as well as the high volume of landings (bivalve landings in 2006 were around 2500 t), make the dredge fishery one of the most important local artisanal fisheries. Over the last decade great attention has been given to enhancing *Spisula solida* stocks (Joaquim et al. 2008) and to reducing the impact of dredging on the macrobenthic fauna, as well as improving the selectivity and efficiency of the fishing gears. This resulted in the development of a new dredge (see review by Gaspar and Chícharo 2007). Nevertheless, few studies have focused on bycatch and discard mortality. Palma et al. (2003) evaluated the flatfish discards from the southern coast of Portugal and found that they were a small proportion of bycatch. Gaspar and Monteiro (1999) reported high mortalities of juvenile bivalves resulting from deck exposure. Moreover, in this fishery, onboard sorting of the catches and discard normally occurs outside fishing areas (Gaspar et al. 2002). The relocation of benthic fauna by discarding over inappropriate bottom types may increase discard mortality and scattering bycatch may play a role in restructuring communities (Veale et al. 2001). Hitherto, there is no documented quantitative account of bycatch composition, as well as there is no information on discard mortality from the Portuguese bivalve dredge fishery. Gear characteristics vary considerably among dredges used in Portugal and it is expected that this would affect the amount and composition of bycatch, and consequently discard mortality. In the present work, catches from three different dredges currently used in the *S. solida* commercial fishery were compared in order to characterize bycatch and to estimate discard mortality.

2 Materials and methods

2.1 Study area

The experiments were carried out on the Sines region off Lagoa de Santo André, southwestern coast of Portugal (Fig. 1), an area that has not been fished during the last decade. Surveys were undertaken in May 2006 using the *RV "Diplodus"*. Tows were carried out on clean sandy bottoms at depths ranging from 5 to 10 m, which corresponds to the depth range of the bivalve dredge fishery in this area.

2.2 Sampling

In the Portuguese dredge fishery, only mechanical dredges are allowed. These dredges are made of a rigid iron structure with a toothed lower bar, and a collecting system. To

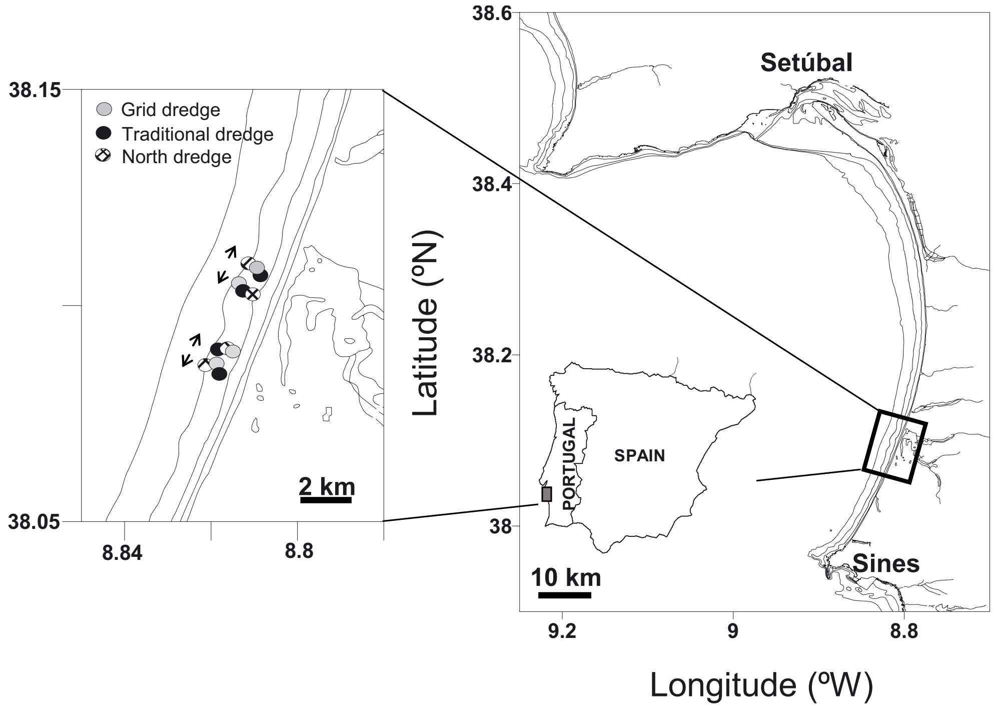

Fig. 1. Sines region (southwestern coast of Portugal). Rectangle shows the location of the study area. Arrows indicate the direction of the tows.

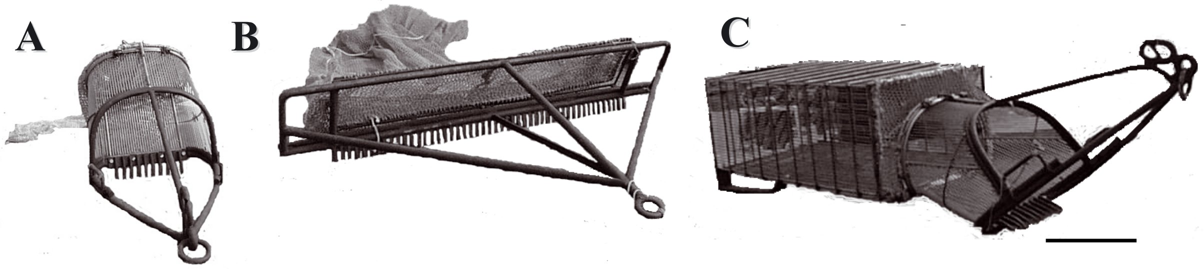

Fig. 2. Dredges used in the *Spisula solida* fishery. A: Traditional dredge (TD); B: North dredge (ND); C: Grid dredge (GD).

Table 1. Gear specifications (see Fig. 2).

Gear specifications			
	TD (A)	ND (B)	GD (C)
Weight (kg)	40	95	80
Dredge mouth			
Length (cm)	64	193.5	64
Height (cm)	54	28.5	54
Tooth bar			
Tooth length (cm)	15	12	15
Tooth spacing (cm)	2.2	2	2.2
Retention			
Net bag length (cm)	250	450	-
Mesh size (cm)	2.5	2.5	-
Grid spacement (cm)	-	-	0.8
Mesh shape	Diamond	Diamond	-

include all clam dredges used by the commercial fleet that operates along the Portuguese coast, three types of dredges (Fig. 2, Table 1) were used: the north dredge (ND), the traditional dredge (TD) and the grid dredge (GD). The main differences between the dredges used in the *S. solida* fishery relate to the shape and length of the dredge mouth and the collecting system. In the ND and TD, the catch is retained in a diamond mesh net bag, whilst in the GD the catch is retained in a metallic grid cage (Fig. 2). For each dredge type, a total of four tows were performed. Dredges were towed for 15 min at a mean speed of 2 knots, following the usual fishing procedures. In order to estimate the swept area for each dredge, the towing distance was recorded with a DGPS. The average swept area for the ND, TD and GD was 1390, 460 and 420 m^2 per 15 min tow, respectively. At the end of each tow, the catch was sorted on deck into target (landing catches) and non-target (bycatch) species. All individuals of the target species that were damaged or below the minimum landing size (MLS-25 mm shell length) were assigned to bycatch. To estimate bycatch mortality induced by each dredge, the extent of damage sustained was recorded for each organism caught using a four score scale

(Gaspar et al. 2003a):

- Score 1, individuals in perfect condition;
- Score 2, individuals slightly damaged;
- Score 3, individuals heavily damaged, and
- Score 4, dead individuals.

This was visually assessed by the same person on all occasions, immediately after sampling operations on board. It was assumed that all individuals scored as 3 would die. Therefore individuals scored as 3 and 4 were used to quantify direct mortality of discarded bycatch.

2.3 Data analysis

Prior to any analysis, abundance data was square root transformed. The relationships between samples were examined by non-metric multidimensional scaling (MDS) and clustering data (unweighed pair group average), based on Bray-Curtis (or Czekanowski according to Yoshioka 2008) similarity coefficient. Analysis of similarity (ANOSIM) was performed to detect significant differences in dredges bycatch composition. SIMPER analysis (similarity percentage – species contribution) was undertaken in order to highlight the taxa that most contributed to the dissimilarity between dredges. Multivariate analyses were carried out using PRIMER v5.0 (Clark and Warwick 1994). Differences in the abundance of the species that most contributed (>10%; n. ind. > 10 per treatment) to the dissimilarity between dredges were determined by one way ANOVA (Model 1, Fixed effects). This test was also used to compare the estimated amount of dead bycatch organisms (mean weight and number) by daily quota (200 kg *S. solida* per boat) among the three dredge types. ANOVA was also used to assess differences in bycatch proportion and bycatch mortality, after arc-sine transformation of data. Whenever ANOVA assumptions were not met the Kruskal-Wallis ANOVA was used. When significant differences were detected, the multiple comparison test of Student Newman Keuls (S-N-K) was performed. ANOVA and K-W ANOVA analyses were performed using STATISTICA v6.0.

3 Results

3.1 Catch composition

The catch composition for the three dredges is presented in Table 2. For all dredges, the target species comprised the largest part of the catch. For total abundance, the ratio of bycatch to *Spisula solida* was low, 0.22:1, 0.10:1 and 0.33:1 for the ND, GD and TD, respectively. For biomass, the ratio was 0.15:1, 0.14:1 and 0.32:1 for the ND, GD and TD, respectively. Bivalves were the most represented bycatch group with 7 species, followed by crustaceans with 5 species.

In terms of total abundance, the percentage of bycatch was 9, 18 and 25% for the GD, ND and the TD, respectively (Table 2). Statistical differences were observed (ANOVA: $df = 2$, $F = 7.091$, $p = 0.014$) between the GD and both the TD ($\text{SNK}_{\text{GDvsTD}}$: $p < 0.05$) and the ND ($\text{SNK}_{\text{GDvsND}}$: $p < 0.05$). Average bycatch in weight ranged between 1.664 kg (ND) and 6.498 kg (TD) per 15 min tow, with differences recorded between all dredges (ANOVA: $df = 2$, $F = 16.952$, $p < 0.001$). It is noteworthy that the biomass of two species from the GD (*Atelecyclus undecimdentatus* and *Echinocardium cordatum*) and four species from ND (*S. solida*, *Donax vittatus*, *A. undecimdentatus* and *E. cordatum*) and TD (*S. solida*, *D. vittatus*, *A. undecimdentatus* and *Liocarcinus depurator*) amounted to more than 75% of the total bycatch biomass (Table 2).

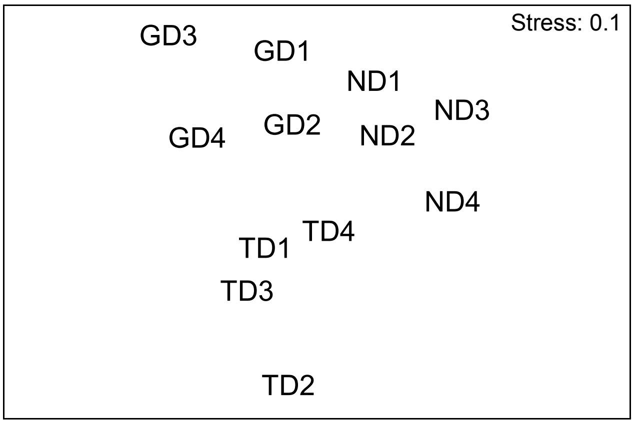

Fig. 3. Non-metric multidimensional scaling diagram of bycatch composition from the three dredges assayed. North dredge (ND); Grid dredge (GD); Traditional dredge (TD).

The MDS plot of bycatch data from all samples collected (Fig. 3), revealed three groups. Each group corresponded to samples from a single dredge, indicating that gear-type affects bycatch composition. The results of the ANOSIM analysis ($R = 0.725$, $p < 0.01$) revealed the existence of significant differences in the bycatch composition between all dredges ($\text{ANOSIM}_{\text{NDvsGD}}$, $R = 0.594$, $p = 0.029$; $\text{ANOSIM}_{\text{NDvsTD}}$, $R = 0.698$, $p = 0.029$; $\text{ANOSIM}_{\text{GDvsTD}}$, $R = 0.885$, $p = 0.029$). The average bycatch dissimilarity observed among dredge groups was 42.2, 45.1 and 45.5% to $\text{ND}_{\text{vs}}\text{GD}$, $\text{ND}_{\text{vs}}\text{TD}$ and $\text{GD}_{\text{vs}}\text{TD}$, respectively. These dissimilarities reflect the way the dredges selected/retained bycatch species. The species that most contributed to the dissimilarities found among dredges are shown in Table 3. Within the bycatch, *D. vittatus*, undersized *S. solida*, *A. undecimdentatus* and *L. depurator* were the taxa that most contributed to the differences observed between dredges (Table 3). Significant differences were recorded in the number of undersized *S. solida* retained by the three dredges (ANOVA: $df = 2$, $F = 5.651$; $p = 0.025$). The GD and ND retained a lower number of undersized *S. solida* compared to the TD ($\text{SNK}_{\text{GDvsTD}}$: $p < 0.05$; $\text{SNK}_{\text{NDvsTD}}$: $p < 0.05$). Between the GD and ND no significant differences were detected ($\text{SNK}_{\text{GDvsND}}$: $p > 0.05$). Concerning *D. vittatus*, significant differences were found regardless the dredge combination tested (ANOVA: $df = 2$, $F = 127.5$, $p < 0.001$). Almost all *D. vittatus* individuals escaped during the tow through the metallic grid of the GD. The abundance of *D. vittatus* in bycatch was higher in the ND compared to TD.

Within the crustaceans, the sandy crab (*A. undecimdentatus*) was the species that contributed most to the differences found amongst dredges. SIMPER analysis showed that the

Table 2. Catch Composition (in number and weight) from the three dredges assayed and % contribution of each taxon to total catch and bycatch (15 min tow). ND: North dredge; GD: Grid dredge; TD: Traditional dredge.

	Total number			Mean number			Contribution to total			Contribution to bycatch			Total weight (g)			Mean weight (g)			Contribution to total			Contribution to bycatch		
	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD
Landing capture																								
Spisula solida	6111	13 797	11 361	1528	3449	2840	82	91	75	-	-	-	44 538	111 666	82 029	11 135	27 917	20 507	87	87	76	-	-	-
Bycatch																								
Bivalvia																								
Spisula solida	144	267	951	36	67	238	2	2	6	11	20	25	1202	1107	3678	300.60	277	920	2	1	3	18	7	14
Donax vittatus	591	9	1650	148	2	413	8	0	11	44	1	44	2025	35	5742	506	9	1436	4	0	5	30	0	22
Tellina tenuis	3	3	51	1	1	13	0	0	0	0	0	1	3	1	55	1	0	14	0	0	0	0	0	0
Ensis siliqua	3	9	45	1	2	11	0	0	0	0	1	1	9	105	847	2	26	212	0	0	1	0	1	3
Chamelea striatula	0	0	3	-	-	1	-	-	0	-	-	0	0	0	9	-	-	2	-	-	0	-	-	0
Dosinia exoleta	0	3	0	-	-	-	-	0	-	-	0	-	0	39	0	-	10	-	-	0	-	-	0	-
Mactra corallina stultorum	3	30	24	1	8	6	0	0	0	0	2	1	34	280	257	9	70	64	0	0	0	1	2	1
Total	744	321	2724	186	81	681	10	2	18	55	24	73	3274	1566	10 588	818	392	2647	6	1	10	49	10	41
Crustacea																								
Atelecyclus undecimdentatus	483	843	609	121	211	152	7	6	4	36	62	16	1417	10 836	8546	354	2709	2137	3	9	8	21	67	33
Liocarcinus depurator	48	27	342	12	7	86	1	0	2	4	2	9	324	134	4412	81	33	1103	1	0	4	5	1	17
Polybius heslowi	6	24	21	2	6	5	0	0	0	0	2	1	51	245	305	13	61	76	0	0	0	1	2	1
Pagurus spp.	3	0	0	1		0	0	0	0	0	0	0	21	0	0	5	-	-	0	0	0	0	0	0
Squilla mantis	0	0	6	-	-	1	-	-	-	-	0	0	-	-	11	-	-	3	-	-	0	-	-	0
Total	540	894	978	135	224	244	7	6	7	40	66	26	1813	11 215	13 274	453	2804	3319	4	9	12	27	70	51
Echinoidea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Echinocardium cordatum	51	144	15	13	36	4	1	1	0	4	11	0	1234	3285	244	309	821	61	2	3	0	19	20	1
Cephalopoda																								
Sepia officinalis	0	0	3	-	-	1	-	-	0	-	-	0	-	-	690	-	-	173	-	-	1	-	-	3
Annelida																								
Polychaeta n.d.	0	0	12	-	-	3	-	-	0	-	-	0	-	-	24	-	-	6	-	-	0	-	-	0
Osteichthyes																				-				
Citharus linguatula	3	0	3	1	-	1	0	-	0	0	-	0	41	-	357	10	-	89	0	-	0	1	-	1
Dicologoglossa cuneata	0	0	6	-	-	2	0	-	0	0	-	0	0	-	816		-	204	0	-	1	0	-	3
Trachinus vipera	15	0	0	4	-		0	-	0	1	-	0	294	-	0	74	-	-	1	-	0	4	-	0
Total	18	0	9	5	-	2	0	-	0	1	-	0	335	-	1173	84	-	293	1	-	1	5	-	5
Total bycatch	1353	1359	3741	338	340	935	18	9	25	100	100	100	6656	16 066	25 993	1664	4017	6498	13	13	24	100	100	100
Total catch	7464	15 156	15 102	1866	3789	3776	0	0	0	0	0	0	51 194	127 732	108 022	12 799	31 933	27 006	0	0	0	0	0	0

Table 3. SIMPER results for the bycatch species having the greatest contribution to the dissimilarity between dredges. ND: North dredge; GD: Grid dredge; TD: Traditional dredge.

Species	Average dissimilarity	Contribution (%)
ND vs GD		
Donax vittatus	7.76	18.4
Atelecyclus undecimdentatus	5.74	13.6
Mactra corallina stultorum	5.24	12.4
Echinocardium cordatum	4.08	9.7
Polybius henslowi	3.92	9.3
Liocarcinus depurator	3.78	9.0
ND vs TD		
Donax vittatus	4.89	10.8
Atelecyclus undecimdentatus	4.69	10.4
Ensis siliqua	4.18	9.3
*Spisula solida**	3.92	8.7
Tellina tenuis	3.72	8.3
GD vs TD		
Donax vittatus	10.21	22.4
Liocarcinus depurator	4.89	10.8
Ensis siliqua	3.88	8.5
Echinocardium cordatum	3.69	8.1
Tellina tenuis	3.54	7.8
*Spisula solida**	3.03	6.7
Atelecyclus undecimdentatus	3.00	6.6

*Undersized and/or damaged.

ND retained a significantly lower number of the latter species than GD and TD (K-W test: $H = 7.53$; $df = 2$; $N = 12$, $p = 0.023$; $\mathrm{SNK}_{\mathrm{NDvsTD}}$: $p < 0.05$; $\mathrm{SNK}_{\mathrm{GDvsND}}$: $p < 0.05$). Between the GD and TD significant differences were not found ($\mathrm{SNK}_{\mathrm{GDvsTD}}$: $p > 0.05$). The SIMPER analysis also highlighted a minor contribution of other species to the differences found among dredges.

3.2 Mortality of discarded bycatch

The overall estimated percentage of dead bycatch (Fig. 4) differed significantly among dredges (ANOVA: $df = 2$, $F = 11.876$; $p = 0.003$). Mortality varied between GD and both ND (S-N-$\mathrm{K}_{\mathrm{NDvsGD}}$: $p < 0.05$) and TD (S-N-$\mathrm{K}_{\mathrm{TDvsGD}}$: $p < 0.05$). No differences were observed between the two dredges equipped with a net bag (S-N-$\mathrm{K}_{\mathrm{NDvsTD}}$: $p > 0.05$). The mean proportion of bycatch mortality was lower for the ND (10%) and TD (20%) than for GD (36%). Nevertheless, no significant differences were found between dredges when *D. vittatus* (a very resilient species to dredging) was removed from the analysis (ANOVA: $df = 2$, $F = 1.343$; $p = 0.31$). Moreover, overall mortality increased for ND and TD when *D. vittatus* was excluded from the bycatch (Fig. 4).

Table 4 summarizes the mean percentage of dead individuals in the bycatch. The highest mortalities occurred in the same taxa regardless of dredge type. The bivalves *S. solida*, *E. siliqua* and *Mactra corallina stultorum*, the sea urchin *E. cordatum*, the crabs *A. undecimdentatus* and *Polybius henslowi*, were the most affected species. Total mortality in number (individuals per 15 min tow) differed significantly between gear types (ANOVA: $df = 2$, $F = 26.30$; $p < 0.001$), being higher for TD (190.5 ± 36.5 ind.) and GD (121.5 ± 19.7 ind.) than for ND (35.3 ± 48.1 ind.) (S-N-K: $p < 0.001$ for all pairwise dredge combinations). The percentage mortality of each bycatch species varied among dredges (Table 3). In the case of ND and TD, overall bycatch mortality (59.5% and 52.7%, respectively) was mainly due to two bivalve species (*S. solida* and *D. vittatus*). The sea urchin *E. cordatum* (12.8%) also contributed to the high bycatch mortality in ND. In the case of the GD, overall bycatch mortality (70%) was mainly due to *A. undecimdentatus* (57%) and *E. cordatum* (12%).

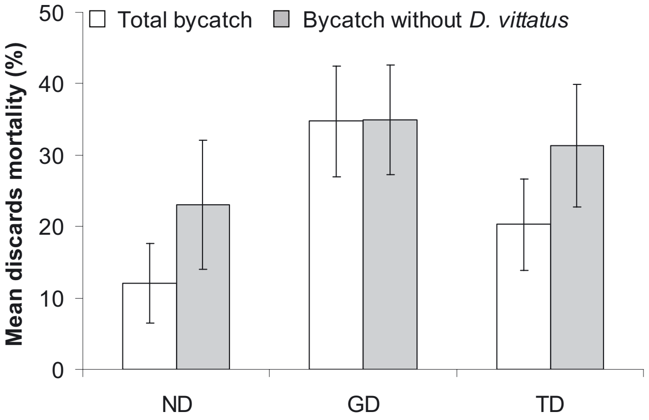

Fig. 4. Comparison of the mean mortality of discarded bycatch, with and without *Donax vittatus*. Error bars represents one standard deviation. North dredge (ND); Grid dredge (GD); Traditional dredge (TD).

Taking into consideration the mean fishing yield (kg per 15 min tow) for *S. solida* obtained for each dredge (GD: 27.92 ± 5.68 kg, TD: 20.51 ± 3.83 kg, and ND: 11.13 ± 2.35 kg) and that the solid surf clam fishery is managed by a daily quota of 200 kg of *S. solida* per boat, the estimated bycatch in weight corresponding to daily quota was significantly higher (K-W test: $H = 5.69$; $df = 2$; $N = 12$, $p = 0.048$) for the TD (65 ± 26 kg per 200 kg of *S. solida*). This value was roughly twice that obtained for ND (35 ± 10 kg per 200 kg of *S. solida*) and GD (29±7 kg per 200 kg of *S. solida*) (S-N-$\mathrm{K}_{\mathrm{TDvsND}}$: $p < 0.05$; S-N-$\mathrm{K}_{\mathrm{TDvsGD}}$: $p < 0.05$) (Fig. 5). The estimated dead bycatch in weight to reach the daily quota was also significantly higher (K-W test: $H = 6.00$; $df = 2$; $N = 12$, $p = 0.044$) for TD (18 ± 14 kg per 200 kg of *S. solida*) than for both ND (5 ± 6 kg per 200 kg of *S. solida*) and GD (4 ± 2 kg per 200 kg of *S. solida*) (Fig. 5). The area that has to be dredged to attain the daily quota was 24 966 m^2, 4486 m^2 and 3008 m^2 for ND, TD and GD, respectively.

4 Discussion

Although *S. solida* was the main species caught, a considerable bycatch was also retained by the dredges. The bycatch composition varied considerably among dredges, both in terms of presence/absence and abundance of species, as a consequence of the selective properties of the gears. In fact, selectivity is directly related to the different retention mechanisms used (net bag *versus* grid cage) and to the way the

Table 4. Mean number and mean proportion of dead bycatch individuals that entered the dredges, by taxon and gear type. ND: North dredge; GD: Grid dredge; TD: Traditional dredge.

	Mortality (no.)			Mortality (%)			Contribution to dead bycatch (%)			Mortality (no. to reach quota)		
	ND	GD	TD	ND	GD	TD	ND	GD	TD	ND	GD	TD
Bivalvia												
Spisula solida	14.3	28.5	70.5	39.6	42.7	29.7	40.4	23.5	37.0	1353.8	627.0	2115.0
Donax vittatus	6.8	0.0	30.0	4.6	0.0	7.3	19.1	0.0	15.7	641.3	0.0	900.0
Tellina tenuis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ensis siliqua	0.8	2.3	9.0	100.0	100.0	80.0	2.1	1.9	4.7	71.3	49.5	270.0
Chamelea striatula	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dosinia exoleta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mactra corallina stultorum	0.0	2.3	3.0	0.0	30.0	50.0	0.0	1.9	1.6	0.0	49.5	90.0
Total	21.8	33.0	112.5	11.7	41.0	16.5	61.7	27.2	59.1	2066.3	726.0	3375.0
Crustacea												
Atelecyclus undecimdentatus	6.0	69.8	44.3	5.0	33.1	29.1	17.0	57.4	23.2	570.0	1534.5	1327.5
Liocarcinus depurator	0.8	0.8	27.8	6.3	11.1	32.5	2.1	0.6	14.6	71.3	16.5	832.5
Polybius heslowi	1.5	3.0	3.0	100.0	50.0	57.1	4.3	2.5	1.6	142.5	66.0	90.0
Pagurus spp.	0.0	-	-	0.0	-	-	0.0	-	-	0.0	-	-
Squilla mantis	-	-	0.0	-	-	0.0	-	-	0.0	-	-	0.0
Total	8.3	73.5	75.0	6.1	32.9	30.7	23.4	60.5	39.4	783.8	1617.0	2250.0
Echinoidea												
Echinocardium cordatum	4.5	15.0	2.3	35.3	41.7	60.0	12.8	12.3	1.2	427.5	330.0	67.5
Cephalopoda										0.0	0.0	0.0
Sepia officinalis	-	-	0.8	-	-	100.0	-	-	0.4	-	-	22.5
Annelida										0.0	0.0	0.0
Polychaeta n.d.	-	-	0.0	-	-	0.0	-	-	0.0	-	-	0.0
Osteichthyes										0.0	0.0	0.0
Citharus linguatula	0.8	-	-	100.0	-	-	2.1	-	-	71.3	-	-
Dicologoglossa cuneata	-	-	0.0	-	-	0.0	0.0	-	0.0	0.0	-	0.0
Trachinus vipera	0.0	-	0.0	0.0	-	0.0	0.0	-	0.0	0.0	-	0.0
Total	0.8	0.0	0.0	16.7	-	0.0	2.1	0.0	0.0	71.3	0.0	0.0
Total dead bycatch	35.3	121.5	190.5							3348.8	2673.0	5715.0

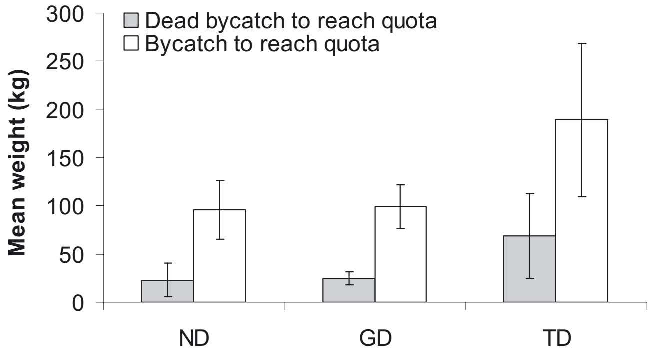

Fig. 5. Estimated bycatch and dead bycatch (weight) to reach the daily quota. Error bars represents one standard deviation. North dredge (ND); Grid dredge (GD); Traditional dredge (TD).

dredges behaved during the tow. In our study, the estimated total weight of bycatch ranged between 9% (GD) and 25% (TD) of the weight of the target species caught. These proportions of bycatch were lower than the one reported by Garcia et al. (2006) for the scallop fishery in west Iceland. In the smooth clam (*Callista chione*) fishery, Gaspar et al. (2001) reported bycatch proportions of 25% and 48% for GD and TD, respectively. Several reasons may explain these differences in the bycatch proportion, namely, gear specifications and structure and composition of benthic communities.

Portuguese clam dredges were designed to catch bivalves according to their size (TD and ND) or their thickness (GD). In the case of bivalves, GD retained a very small quantity compared to the other two dredges. Almost all *D. vitattus* and undersized *S. solida* that entered the GD escaped during the haul. In contrast, bycatch from TD and ND was composed of a significant proportion of bivalves, including juveniles of the target species. This can likely be explained by the closing of the mesh during the haul, which impeded the escape of individuals through the mesh and illustrates the way in which different retention mechanisms can influence bivalves' bycatch composition. Although, it was not clear how selectivity affected the catch composition of other invertebrate groups, their morphology is certainly an important factor. Given that there is considerable morphological diversity in the bycatch, it is difficult to design a system that can be simultaneously selective for all species. For instance, despite being highly selective for one bivalve species, the GD retained more *A. undecimdentatus* than the other dredge types, because this crab was unable to pass through the grid. As the mesh of the net bag stretches and compresses shortly after beginning the tow, a considerable percentage of these crabs were expected to be caught by the ND and TD, but this did not occur. A possible explanation is the clogging of the dredge mouth, which impeded the crabs entering the net bag. Since the sediment that enters the dredge does not escape rapidly through the meshes, a sand buffer is formed in front of the dredge mouth, decreasing dredge efficiency and consequently reducing the number of invertebrate macrofauna entering the dredge (see review by Gaspar and Chícharo 2007).

Technical modifications and developments have been implemented in several fishing gears, aiming the improvement of selectivity and the reduction of bycatch and discard mortality (Michael et al. 1990; Farmer et al. 1998; Kennelly et al. 1998). Enhancing the immediate escape of individuals during the tow would significantly increase the likelihood of their survival (Broadhurst and Kenelly 1997). This is the case with the GD, which is more selective than the other two dredges, allowing a large number of individuals to escape during the tow, reducing indirect mortality due to handling, deck exposure and predation. This result is related to differences in the geometry of the gear during dredging (Gaspar and Chícharo 2007). When a net bag is used, the mesh stretches while the dredge is being towed, impeding the escape of organisms through the mesh. Therefore, a high proportion of the individuals that entered the dredge were retained. In contrast, when a metallic grid is used, selection of the captured individuals occurs throughout the tow. Selectivity of TD and ND dredges may be improved by (1) reducing the twine thickness and stiffness, which lowers the mesh resistance to opening (Suuronen and Sardà 2007), (2) by restricting the number of meshes, or (3) by hanging the net bag on ropes with a length lower than the stretched length of the net bag (Robertson and Shanks 1989).

Reducing the bycatch does not necessarily imply a decrease in the proportion of dead bycatch. Despite the significantly lower percentage of bycatch in the GD, mortality was higher than in ND and TD. This was due to the presence of a high number of *A. undecimdentatus*, which are more sensitive to the GD fishing operations. Nevertheless, the highest mortalities were recorded for the same species (*E. siliqua, E. cordatum* and *P. henslowi*) regardless of gear type. Apparently, the use of a net bag to retain the catch reduces bycatch mortality, but also significantly decreases the fishing yields of the target species, particularly in the ND, since catch efficiency of meshed dredges is lower than that of GD (Gaspar et al. 2003a). As a consequence of the lower efficiency of ND, the area dredged to attain the daily quota was four and six times that covered by TD and GD, respectively, corroborating the dredge efficiencies reported by Gaspar et al. (2003a). If a larger fishing area is affected, then it is quite conceivable that the number of macrobenthic individuals affected due to physical disturbance would increase proportionally.

Since the *S. solida* fishery is regulated by a daily quota per vessel, another important factor to consider is the corresponding amount of bycatch and discard mortality. Taking into account the mean fishing yield obtained for each dredge, the estimated bycatch from the TD by daily quota is twice that resulting from both ND and GD. Moreover, the estimated mortality of discarded bycatch in weight to reach the daily quota was also higher in TD than in ND and GD. Thus, considering all these issues, the cumulative effect of fishing effort in the long-term (expressed as the amount of bycatch and dead bycatch) could be reduced by using the GD.

The grid cage indirectly acts as a bycatch reduction device, because it reduces the catch of unwanted species, while maximizing catches and reducing fishing time and towed area. Moreover, Gaspar et al. (2003) reported that damage to uncaught individuals (individuals that were in contact with the dredge but that were not retained) was inversely correlated to gear efficiency. That is, the higher the efficiency, the lower the mortality inflicted to uncaught individuals. Thus, there are obvious advantages in developing dredges with rigid retention structures, such as metallic grids, which are more selective and efficient than dredges that use flexible retention methods, such as mesh net bags. The importance of improving fishing efficiency in output-controlled fisheries (as is the case of the Portuguese bivalve fisheries) was also reported by Robert (2002) and Howard (2004) for scallop fisheries. The reduction of bycatch and discard mortality is expected to enhance the maintenance of both target and non-target species populations. Notwithstanding, our results showed that, even in the GD, the proportion of discarded bycatch was still high, indicating that selectivity should be improved. As in the case of trawls (see reviews by Broadhurst 2000; Broadhurst et al. 2007 and references therein), the use of bycatch reduction devices inside the cage, associated with grid windows, could be an important step forward.

Despite GD offers several advantages, compared to the other two dredges, our results showed differences in the species that are most affected by dredging which depend on their vulnerability to each dredge type. Therefore, the use of a certain dredge type causes a "selective" and continuous removal of specific taxa from an area, which may lead to local long-term changes in diversity and faunal structure of benthic communities. Collie et al. (2000) concluded that the removal of megafauna species reduced the complexity of the benthic community. Moreover, heterogeneity is an important component of the functioning of ecological systems (Kolosa and Pickett 1991), and reductions in heterogeneity over large spatial and temporal scales have implications for the maintenance of diversity and stability at the population, community and ecosystem scales (Pimm 1991). Bycatch megafauna might be the best indicator of fishing effects, because in general they are more vulnerable to fishing than smaller species, and as slower growing organisms they tend to take a longer time to recover (Collie et al. 2000). Clam fisheries must be goal-oriented and adaptive to the evolution of macrofauna communities to allow maximizing fishing yields, but avoiding disruptions in the structure of benthic communities. As long-term effects of fishing are difficult to preview, the exploitation strategies might include the use of different dredges, thereby diversifying bycatch and consequently avoiding the cumulative removal and death of specific macrofauna taxa. Nevertheless, studies should be carried out to ascertain if this strategy is beneficial for benthic communities.

Acknowledgements. We would like to thank João Tata Regala, Jorge Ramos, Paulo Vasconcelos and two anonymous referees for reviewing and providing useful comments that significantly improved the manuscript. Thanks are also due to the crew of the *RV "Diplodus"* for their skillful handling of the boat and fishing gear.

References

Borges T.C., Erzini K., Bentes L., Costa M.E., Gonçalves J.M.S., Lino P.G., Pais C., Ribeiro J., 2001, By-catch and discarding practices in five Algarve (Southern Portugal) métiers. J. Appl. Ichthyol. 17, 104–114.

Broadhurst M.K., 2000, Modifications to reduce by-catch in prawn trawls: a review and framework for development. Rev. Fish Biol. Fish. 10, 27–60.

Broadhurst M.K., Kenelly S.J., 1997, Effects of circumference of codends and new designs of square-mesh panel in reducing unwanted by-catch in the New South Wales oceanic prawn trawl fishery, Australia. Fish. Res. 27, 203–214.

Broadhurst M.K., Kennely S.J., Gray C., 2007, Strategies for improving the selectivity of fishing gears. In: Kennelly S. (Ed.), By-catch reduction in the world's fisheries. Dordrecht, Springer, pp. 1–21.

Caddy J.F., 1968, Underwater observations on scallop (*Placopecten magellanicus*) behaviour and drag efficiency. J. Fish. Res. Board Can. 25, 2123–2141.

Campbell M., Courtney T., 2006, Benefits of square mesh codends in Queenslands scallop and prawn trawl fisheries. Bycatch Comm. Network Newslett. 3, 13–15.

Chapman C.J., Mason J., Kinnear J.A.M., 1977, Diving observations on the efficiency of dredges used in the Scottish fishery for the scallop, *Pecten maximus* (L.). Scott. Fish. Res. Rep. 10.

Clark K.R., Warwick R.M., 1994, Change in Marine Communities: an approach to statistical analysis and interpretation. Natural Environment Research Council, Plymouth Marine Laboratory, Plymouth.

Collie J.S., Hall S.J., Kaiser M.J., Poiner I.R., 2000, A quantitative analysis of fishing impacts on shelf-sea benthos. J. Anim. Ecol. 69, 785–799.

Dare P.J., Key D., Darby C.D., Connor P.M., 1993, The efficiency of spring-loaded dredges used in the western English Channel fishery for scallops, *Pecten maximus* (L.). ICES CM1993/B:15.

Dayton P.K., Thrush S.F., Agardy M.T., Hofman R.J., 1995, Environmental effects of marine fishing. Aquat. Conserv. 5, 205–232.

De Groot S.J., 1984, The impact of bottom trawling on benthic fauna of the North Sea. Ocean Manag. 9, 177–190.

Erzini K., Costa M.E., Bentes L., Borges T.C., 2002, A comparative study of the species composition of discards from five fisheries from the Algarve (southern Portugal). Fish. Manage. Ecol. 9, 31–40.

Farmer M.J., Brewer D.T., Blaber S.J.M., 1998, Damage to selected fish species escaping from prawn trawl codends: a comparison between square-mesh and diamond-mesh. Fish. Res. 38, 73–81.

Garcia E.G., Ragnarsson S.Á., Eiríksson H., 2006, Effects of scallop dredging on macrobenthic communities in west Iceland. ICES J. Mar. Sci. 63, 434–443.

Gaspar, M.B., Castro, M., Monteiro, C.C., 1999, Effect of tooth spacing and mesh size on the catch of the Portuguese clam and razor clam dredge. ICES J. Mar. Sci. 56, 103–110.

Gaspar M.B., Chícharo L.M., 2007, Modifying dredges to reduce by-catch and impacts on the benthos. In: Kennelly S. (Ed.), By-catch reduction in the world's fisheries. Dordrecht, Springer, pp. 95–140.

Gaspar M.B., Dias M.D., Campos A., Monteiro C.C., Santos M.N., Chicharo A., Chicharo L., 2001, The influence of dredge design on the catch of *Callista chione* (L. 1758). Hydrobiologia 465, 153–167.

Gaspar M.B., Leitão F., Chicharo L., Santos M.N., Monteiro C.C., 2003a, A Comparison of direct mortality inflicted on macrofaunal organisms by three types of dredges used in the Portuguese clam fishery. ICES J. Mar. Sci. 60, 733–742.

Gaspar M.B., Leitão F., Santos M.N., Sobral M., Chícharo L., Chícharo A., Monteiro C.C., 2003b, Size selectivity of the *Spisula solida* dredge in relation to tooth spacing and mesh size. Fish. Res. 60, 561–568.

Gaspar M.B., Leitão F., Santos M.N, Sobral M., Chícharo L., Chícharo A., Monteiro C.C., 2002, Influence of mesh size and tooth spacing on the proportion of damaged organisms in the catches of the Portuguese clam dredge fishery. ICES J. Mar. Sci. 51, 1228–1236.

Gaspar M.B., Monteiro C.C., 1999, Indirect mortality caused to juveniles of *Spisula Solida* due to deck exposure. J. Mar. Biol. Assoc. UK 79, 567–568.

Gonçalves J.M.S, Stergiou K.I., Hernando J.A., Puente E., Moutopoulos D.K., Arregi L., Soriguer M.C., Vilas C., Coelho R., Erzini, K., 2007, Discards of trammel nets in southern European small-scale fisheries. Fish. Res. 8, 5–14.

Gonçalves J.M.S., Bentes L., Coelho R., Monteiro P., Ribeiro J., Correia C., Lino P.G., Erzini K., 2008a, Non-commercial invertebrate discards in an experimental trammel net fishery. Fish. Manage. Ecol. 15, 199–210.

Gonçalves J.M.S., Bentes L., Monteiro P., Coelho R., Corado M., Erzini K., 2008b, Reducing discards in a demersal purse-seine fishery. Aquat. Living Resour. 21, 135–144.

Hall S.J., 1999, The Effect of Fishing on Marine Ecosystems and Communities. Oxford, Blackwell Science.

Harrington J.M., Myers R.A., Rosenberg A.A., 2005, Wasted fishery resources: discarded by-catch in the USA. Fish Fish. 6, 350–361.

Hauton C., Howell T.R.W., Atkinson R.J.A.; Moore P.G., 2007, Measures of hydraulic dredge efficiency and razor clam production, two aspects governing sustainability within the Scottish commercial fishery. J. Mar. Biol. Assoc. UK, 87, 869–877.

Howard P.J., 2004, Scallop vessels access to groundfish closed areas: a management success. Available online at http//www.nfcc-fisheries.org/cs_pov_2e.html (accessed January 16, 2008).

Jenkins S.R., Brand A.R., 2001, The effect of dredge capture on the escape response of the great scallop, *Pecten maximus* (L.): implications for the survival of undersized discards. J. Exp. Mar. Biol. Ecol. 266, 33–50.

Jenkins S.R., Mullen C., Brand A.R., 2004, Predator and scavenger aggregation to discarded by-catch from dredge fisheries: importance of damage level. J. Sea Res. 51, 69–76.

Joaquim S., Matias D., Lopes B., Arnold W.S., Gaspar M.B., 2008, The reproductive cycle of white clam *Spisula solida* (L.) (Mollusca: Bivalvia): Implications for aquaculture and wild stock management. Aquaculture 281, 43–48.

Kelleher K., 2005, Discards in the world's marine fisheries: an update. FAO Fish. Tech. Pap. 470, 131p.

Kennelly S.J., Liggins G.W., Broadhurst M.K., 1998, Retained and discarded by-catch from oceanic trawling in New South Wales, Australia. Fish. Res. 36, 217–236.

Kolosa J., Pickett S.T.A., 1991, Heterogeneity in Ecological Systems. Ecological Studies N° 86. Springer Verlag, New York.

Maguire J.A., Coleman A., Jenkins S., Burnell G.M., 2002, Effects of dredging on undersized scallops. Fish Res. 56, 155–165.

McLoughlin R.J., Young P.C., Martin R.B., Parslow J., 1991, The Australian scallop dredge: estimates of catching efficiency and associated indirect fishing mortality. Fish Res. 11, 1–24.

Michael K.P., Olsen G.P., Hvid B.T., Cranfield H.J., 1990, Design and performance of two hydraulic subtidal clam dredges in New Zeeland. N.Z. Fish. Tech. Rep. 21, 16p.

Morgan L., Chuenpagdee R., 2003, Shifting Gears: Addressing the Collateral Impacts of Fishing Methods in USA Waters. Island Press Publication Services, Washington DC.

Nashimoto, K., 1984, The selectivity of sunary surf clam dredge. Bull. Jpn. Soc. Sci. Fish. Nissuuishi 50, 1145–1155.

Palma J., Reis C., Andrade J.P., 2003, Flatfish discarding practices in bivalve dredge fishing off the south coast of Portugal (Algarve). J. Sea Res. 50, 129-137.

Pauly D., Christensen V., 2002, Primary production required to sustain global fisheries. Nature 374, 255–257.

Philippart C.J.M., 1998, Long-term impact of bottom fisheries on several by-catch species of demersal benthic fish and benthic invertebrates in the South-Eastern North Sea. ICES J. Mar. Sci. 55, 342–352.

Pimm S.L., 1991, The Balance of Nature? Ecological issues in the conservation of species and communities. University of Chicago Press, Chicago.

Rambaldi E., Bianchini M.L., Priore G., Prioli G., Mietti N., Pagliani T., 2001, Preliminary appraisal of an innovative hydraulic dredge with vibrating and sorting bottom on clam beds (*Chamelea gallina*). Hydrobiologia 465, 1573–5117.

Robert G., 2002, Impact of multibeam survey on scallop fishing efficiency and stock assessment. Review Canadian Offshore Scallop Industry Mapping Group, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, pp. 40–41.

Robertson J.H.B., Shanks A.M., 1989, Further studies of the size selection of *Nephrops* by different cod-ends. Scottish Fisheries Working Paper, no. 1/89.

Roosenburg W.M., Jason P.G., 1999, Impact of a by-catch reduction device on diamondback terrapin and blue crab capture in crab pots. Ecol. Appl. 10, 882–889.

Suuronen P., Sardà F., 2007, By-catch reduction techniques in European fisheries: traditional methods and potential innovations. In: Kennelly S. (Eds.), By-catch reduction in the world's fisheries, Dordrecht, Springer, pp. 37–74.

Valdemarsen J.W., Suuronen P., 2003, Modifying fishing gear to achieve ecosystem objectives. In: Sinclair M., Valdimarsson G. (Eds.) Responsible fisheries in the marine ecosystem, Rome, FAO, pp. 321–341.

Veale L.O., Hill A.S., Hawkins S.J., Brand A.R., 2001, Distribution and damage to the by-catch assemblages of northern Irish scallop dredge fisheries. J. Mar. Biol. Assoc. UK 81, 85–96.