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Damage assessment on the discarded macro-benthic fauna in the Italian striped venus clam (*Chamelea gallina*) fisheries

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Abstract

The striped venus clam fishery in Italy is carried out by means of hydraulic dredges and it is one of the most important socio-economic activities in the Italian fisheries sector. Dredging has traditionally been considered among fishing activities with the greatest impact at the ecosystem level. Here, therefore, we investigated the disturbance level exerted by dredging on the studied area. Also, damage and mortality rates exerted by dredging on the discarded macro-benthic fauna living associated with *Chamelea gallina* during the summer season were investigated using a four-level damage scale, given three different haul time duration (3, 6 and 9 minutes). Despite the fact that macro-benthic fauna represented on average only 4.4% of the total catch, the most represented taxa in terms of both abundance and number were Malacostraca, Bivalvia, and Echinoidea. The analysis of the macro-benthic communities' structure between hauls revealed that the species composition was very similar, and ABC plots together with the Warwick Statistics (W) revealed a moderately disturbed macro-benthic community. No significant difference was found in damage and mortality rates between hauls duration when stratified at taxon or species level. Overall, 61.0% of individuals of the catch were undamaged, whereas 16.1%, 3.7%, and 19.2% displayed slight, intermediate, and severe damage, respectively. We found that soft-shelled or soft-bodied species were the most affected by the harvesting process, whereas thick-shelled or thick-bodied species suffered the slightest damage. In particular, the species suffering major (severe) damage were the sea urchin *Echinocardium cordatum* (84.6%), the bivalves *Mactra stultorum* and *Polititapes aureus* (32.5% and 20.0%, respectively), the crab *Liocarcinus vernalis* (4.0%), and the sea star *Astropecten irregularis* (4.8%). The overall mortality rate of all discarded individuals was 22.9%, with *E. cordatum* showing the highest mortality rate of 96.0%. These findings highlight the importance of guaranteeing the integrity of the entire ecosystem through the adoption of suitable management plans and actions.

Keywords: hydraulic dredging; Chamelea gallina; associated macro-benthic assemblages; discard damage level; mortality rate.

Introduction

Discard comprises the accidental capture of non-target organisms that is returned to sea after a fishing operation (Hall, 1999) because they are unmarketable species: highly damaged species, surplus to quota, or individuals below the Minimum Conservation Reference Size (MCRS) (Kelleher, 2005; Tsagarakis *et al.*, 2014). Discard amount is highly variable depending on the métier and can sometimes represent a large fraction of the total catch (Veale *et al.*, 2001; Kelleher, 2005). Concern has mounted over the years on the impact exerted by the different fishing activities that generate discards (Pranovi *et al.*, 2001; Urra *et al.*, 2017). At the beginning, most of the researches were mainly focused on the impact caused by deep-sea trawling fisheries on bycatch species (Bergmann & Moore, 2001a; Bergmann *et al.*, 2001; Thrush & Dayton, 2002), as well as on commercial ones (Bergmann & Moore, 2001b). However, in recent years, given the increased attention in several parts of the world, some studies started to assess the impact caused by bivalve dredging on shallow coastal fishing grounds on the target species (Moschino *et al.*, 2003; Vasconcelos *et al.*, 2011; Soon & Ransangan, 2019) and on the macro-benthic communities (Gaspar *et al.*, 2002, 2003a,b; Morello *et al.*, 2005a; Urra *et al.*, 2017; Anjos *et al.*, 2018; Vasapollo *et al.*, 2020; Baeta *et al.*, 2021a,b). Dredging has traditionally been considered among fishing activities with the greatest impact on coastal benthic ecosystems (Collie *et al.*, 2000). However, impact also depends on many other factors such as the time scale (i.e. short and long term) (Piersma *et al.*, 2001), the technical features of dredges (e.g. mesh size, tooth length, water jects, etc.), the fishing effort, the local conditions (e.g. depth, type of sediment, benthic community composition, other stress factors) (Collie *et al.*, 2000) and seasonality (Urra *et al.*, 2017; Baeta *et al.*, 2021a). In the long term, removing species and individuals from their habitat through the generation of discards during common fishing practices – *viz.* changing the species' relative abundance and size, together with the population structure of prey and/or predators – can lead to structural and functional disturbances in the ecosystem (Pauly *et al.*, 2002; Thrush & Dayton, 2002). For this reason, a key factor is to have a sound knowledge of the effects derived from fishing at ecosystem level, in order to adopt suitable management plans and actions with the aim of achieving a responsible and sustainable fishing activity.

In this context, the striped venus clam *Chamelea gallina* (Linnaeus, 1758) fishery in Italy is carried out by means of a hydraulic dredge, a fixed-mouth metal cage, equipped with a scraper blade on the lower part, towed over the seabed, ejecting pressurized water from nozzles placed at the dredge mouth and inside the cage to dislodge the marine organisms living in sediments and facilitate their catch (Lucchetti & Sala, 2012). Thus, given the operational method of the gear, it also inevitably catches and damages non-target organisms that occur in the same fishing grounds of the target species. The fleet targeting *C. gallina* consists at present of 615 licensed hydraulic dredges mainly concentrated along the Adriatic coasts (*unpublished data*) where the species thrives at depths of 1 – 12 m (Morello *et al.*, 2006; Lucchetti & Sala, 2012). *C. gallina* is an important faunal component of the shallow soft bottoms in exposed sandy beaches, and, in the Adriatic Sea, the sub-littoral biocenosis of well-sorted fine sands is characterized by a *C. gallina* facies (Vatova, 1949; Froglia, 2000). This is an area subjected to intense hydro-dynamism and environmental fluctuations, and the benthic community associated with the species have an inherent resilience to natural physical disturbance (Macdonald *et al.*, 1996; Kaiser, 1998).

In 2021, the Italian annual production of the striped venus clam fishing sector, which is managed through a rights-based system (Lucchetti *et al.*, 2014, 2021), has been around 21,000 tonnes accounting for over € 67 million in revenues (Italian Ministry, 2022). Taking into consideration the valuable socio-economic importance of *C. gallina* for the Italian fishing sector, a variety of studies investigating a very broad spectrum of aspects have been carried out. Until now, new and updated studies have been recently conducted in the Adriatic Sea on *C. gallina* population, deepening some biological aspects such as its genetic variability (Carducci *et al.*, 2020), age and growth (Mancuso *et al.*, 2019; Bargione *et al.*, 2020), fecundity and reproductive cycle (Bargione *et al.*, 2021a), survivability of undamaged and damaged discarded clams (Bargione *et al.*, 2021b, 2023), as well as the dredge (Petetta *et al.*, 2021) and sieve selectivity (Sala *et al.*, 2017), and the impact exerted by the dredge on the sediment (Lucchetti & Sala, 2012). On the contrary, in the Adriatic Sea, studies related to the impact of hydraulic dredging on macro-benthic communities (Morello *et al.*, 2005b), the damages inflicted on them (Morello *et al.*, 2005a) and on the target species (Marin *et al.*, 2003; Moschino *et al.*, 2003), are older and less up-to-date.

The striped venus clam fishery is currently regulated by detailed European and Italian management plans. Regulation (EC) 1380/2013 of the European Council establishes that in the Mediterranean Sea, where applicable, all catches of species that are subject to catch limits or to a MCRS must be retained on board of fishing vessels, recorded, landed and counted against the quotas. These rules are to be followed unless scientific evidence demonstrates high survival rates of discards, "taking into account the characteristics of the gear, of the fishing practices and of the ecosystem", as is the case in the fishing of bivalve molluscs.

The discard generated by bivalve dredging would not constitute a major problem if the discarded individuals survive after returning to the sea (Gaspar & Chícharo, 2007). However, it is known that dredging affect the benthic communities either directly or indirectly (Pranovi *et al.*, 2001; Gaspar *et al.*, 2002). Indeed, discarded or dislodged organisms left on the dredge path may be killed outright or suffer different damage levels that make them susceptible to predation, whereas those with less damage should be able to recover and survive (Mensink *et al.*, 2000; Gaspar *et al.*, 2003b). The injuries suffered by benthic organisms, which may result in death, can occur during the towing of the dredge on the seabed as specimens hit against the bars of the gear, or because of abrasion inside the dredge, or during the sieving and discarding processes (Veale *et al.*, 2001). Therefore, it is crucial to analyse the composition of discard, as well as its level of damage, in order to propose new strategies to minimize the fishery impact (Urra *et al.*, 2017). This work is aimed at *i)* qualitatively and quantitatively describing the macro-benthic fauna living associated with *C. gallina* during the summer in one of the most important Italian fishing grounds for clams harvesting, *ii*) investigating the similarity of the benthic communities structure and the disturbance level exerted by dredging on the studied area, *iii*) estimating damage and mortality rates on discarded non-target species by means of an *ad hoc* four level damage scale in relation to different hauling time.

Materials and Methods

Study area and biological sampling

Field work was carried out in June 2021 off the mid-western Adriatic Sea in Porto San Giorgio, one of the most important *C. gallina* fishing grounds along the Italian coasts (Fig. 1). One-day fishing trip was carried out on a potential commercial fishing ground next to the 0.3 NM off the coast, a boundary within which clam har-

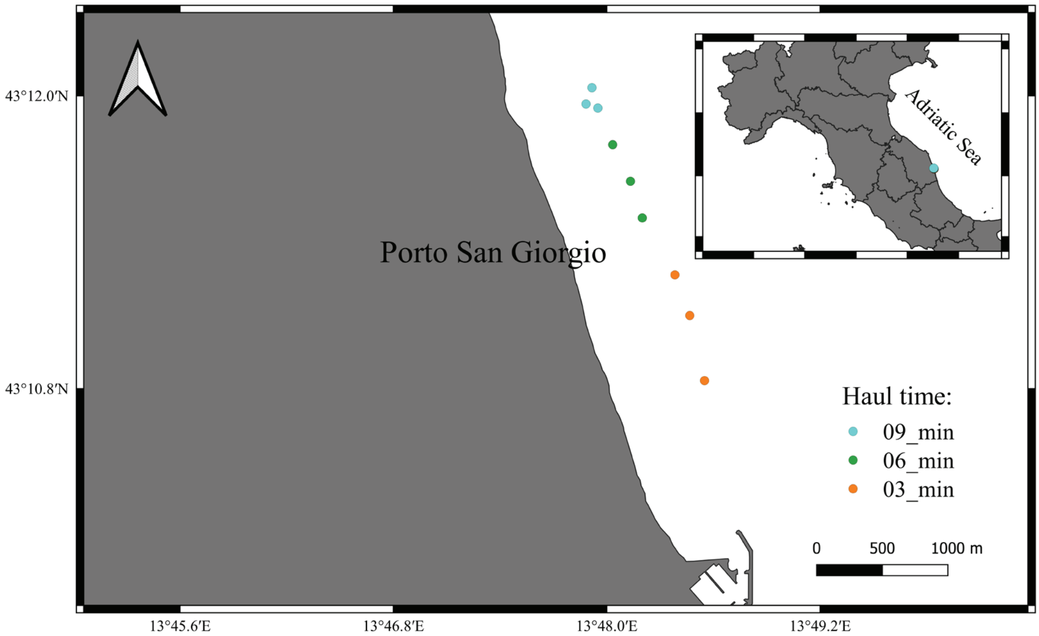

Fig. 1: Map of the sampling area.

vesting is banned by Regulation (EC) 1967/2006 of the European Council. A total of 9 hauls were conducted onboard a commercial hydraulic dredging vessel (88 kW; Length Over All 14.88 m; 22 GT) and close to each other at a depth ranging between and 5 m, which means that no different conditions subsisted between hauls. The haul duration was set at 3, 6 and 9 min (3 replicates each), since the average duration range of commercial hauls was 5-10 min during the sampling period. The average towing speed was maintained at 1.9 knots, which falls within the range of commercial fishing procedures (Romanelli *et al.*, 2009).

At the end of the haul, the dredge was hoisted and its content tipped into the collecting box. The total weight of the catch (Not-sieved, NSV) was recorded and subsequently sieved through the on-board mechanical vibrating sieve that made it possible to sort for *i)* discard (DIS), the fraction retained by the top filter containing the bulkier material (hereafter named in this way, excluding the undersized target species returned to the sea), *ii)* commercial sized clams (COM, ≥ 22 mm TL), the fraction caught by grid 1 and 2, and *iii)* under-sized clams (USZ, < 22 mm TL), the fraction caught by grid 3 and the bottom filter, potentially released to the sea through the waste exhaust pipe which, on this occasion, was blocked (for details on the vibrating sieve, see Sala *et al.*, 2017). Potential non-target small individuals that passed through the grid bars were manually removed and added to the DIS fraction. At the end of the sieving process, the total weights of these three compartments (DIS, COM, USZ) were also recorded. All weights were taken through a marine-type compensation scale (Mod. *Marelec W50/50-D4 marine scale*) with accuracy of 50 g. Subsequently, the DIS fraction was entirely collected to further estimate its composition in terms of abundance (number of individuals/min haul) and biomass (g/min haul).

Laboratory analysis

Before any kind of laboratory analyses, the samples were stored at -22°C and handled gently throughout the process in order to avoid additional damage. In the laboratory, to assess the DIS composition and the damage inflicted by dredging on non-target species for each sample, every specimen was identified at the lowest taxonomic level (whenever possible) and quantified as regards both abundance and biomass (± 0.1 g wet weight). To assess the damage rate, the damage caused to all caught individuals of non-commercial species was assessed using a four-level damage scale: D_0 – intact, D_1 – slightly damaged, D_2 – moderately damaged, D_3 – severely damaged (Table 1). Mortality rate was calculated assuming damage classes D_2 and D_3 expecting to die. Indeed, according to the methodology proposed by Gaspar *et al.* (2001), the damage rate corresponds to the proportion of damaged individuals (i.e. assigned to damage scores D_1 to D_3), whereas the mortality rate corresponds to the proportion of individuals with high likelihood of death (damage score D_2) and dead specimens (damage score D_3).

Data analysis

To describe the overall catch composition, independently from the haul duration, all data was initially standardized per min/haul. All statistical analyses of this investigation were carried out using the free statistical software R version 4.3.2 (R Core Team, 2023). Analysis of similarities (ANOSIM) (Clarke & Warwick, 2001) was used to detect any significant difference in the species composition of DIS between hauls with the function *anosim* of the “vegan” package (v. 2.6-4) (Oksanen *et al.*, 2018). Investigations to determine levels of disturbance on the macro-benthic communities’ structure were carried out by means of the abundance-biomass compari-

Table 1. Damage scale (D_0-D_3) and criteria adopted for scoring different taxa caught as bycatch species during the dredging activity (adapted from Gaspar *et al.*, 2001).

Taxon	*Class damage*			
	D_0	D_1	D_2	D_3
Asteroidea	In good condition, intact	Arms missing	Worn and arm missing / minor disc damage	Major disc damage/dead
Bivalvia	In good condition, intact/repaired	Edge of shell chipped	Hinge broken	Crushed / dead
Echinoidea	In good condition, intact	-	Minor cracks	Crushed / dead
Elasmobranchii	In good condition, intact	-	-	Dead
Gastropoda	In good condition, intact/repaired	Edge of shell chipped	Shell cracked/punctured	Crushed / dead
Malacostraca	In good condition, intact	1-3 legs missing / minor carapace cracks or out of shell and intact (for hermit crabs)	>3 legs missing / major carapace cracks or out of shell and damaged (for hermit crabs)	Crushed / dead
Palaeonemertea	In good condition, intact	-	-	Sectioned

son (ABC) plots (Clarke *et al.*, 2014), and the Warwick Statistics (W; Clarke *et al.*, 2014), both of which were obtained by the *abc* function of the package "forams" (v. 2.0-6). This was followed by the analysis of the impact of haul duration on the DIS fractions. The test for equality of proportions was used to assess differences in the percentage of damage, at each damage level, at taxon and species level given different haul durations (3, 6 and 9 min) (Cornillon *et al.*, 2012), with the command *prop.test* of the basic "stats" package (v. 4.3.2). One-way analysis of variance (ANOVA) was then applied to establish whether haul duration (3, 6 and 9 min) accounted for differences on mortality rate. Before ANOVA, the constant variance assumption was assessed according to Levene's test (Lomax & Hahs-Vaughn, 2013). In case of homoscedasticy, the usual ANOVA was run; if the p value was significant, a *post-hoc* Tukey comparison was performed. In case of heteroscedasticy and significant p value, the Games-Howell *post-hoc* comparisons (Maxwell *et al.*, 2018; Sauder & DeMars, 2019) were carried out by using the function *oneway* of the R "userfriendlyscience" package (v. 0.7.2).

Results

Catch description

On average, the weight of the catch (NSV) considerably increased with haul duration, but it not was the same for the COM fraction, as well as for DIS, which did not vary much between haul times (Supplementary Table S1). The majority of the catch was always represented by the USZ fraction (58.1%, 62.1%, 81.6% in 3, 6 and 9 min hauls, respectively), while COM was higher in 3 and 6 min hauls (ranging between 32.6% and 36.1%) and dropping to 16.3% in 9 min hauls. Overall, the mean catch composition was represented by 28.3% of COM, 4.4% of DIS and 67.3% of USZ. The total catch was mainly composed by the target species (COM+USZ, 95.6%), whereas the discard ratio DR = (USZ + DIS) / NSV showed high values ranging between 0.45 and 0.88, being on average (± standard deviation) 0.72 ± 0.14 and highlighting that the great majority of the catch was always returned to the sea. The details of the hauls are provided in Supplementary Table S1.

Discard description

Within DIS, a total of 7 classes have been identified consisting of 18 species, 1 genera and 1 individual identified only at class level, thus considered a single species. The observed classes within the DIS samples were Asteroidea (1 species), Bivalvia (8 species), Echinoidea (1 species), Elasmobranchii (1 genera), Gastropoda (5 species), Malacostraca (3 species, of which 2 crabs and 1 hermit crab) and Palaeonemertea (1 class, with only one individual). Overall, DIS was dominated by Malacostraca (55.6% and 61.6% of total abundance and biomass, respectively), Bivalvia (23.4% and 21.6%) and Echinoidea (12.7% and 13.0%) (Table 2, Fig. 2). The grey swimming crab (*Liocarcinus vernalis*) and the common heart urchin (*Echinocardium cordatum*) were the only species mainly contributing to the respective fractions of abundance and biomass for Malacostraca and Echinoidea (Table 3). Other taxa were less representative and displayed a lower dominance, such as Asteroidea (2.5% in weight and 6.7% in number), Gastropoda (1.3% in weight and 1.6% in number), Elasmobranchii and Palaeonemertea (≤ 0.1% both in weight and number) (Table 2). The frequency of occurrence (express as percentage, FO%) was calculated

Table 2. Mean standardized abundance and biomass (± standard error, SE) of the faunal groups and non-target discarded species collected during dredging. The mean abundance (%N) and biomass (%B) fractions and the frequency of occurrence (FO%) for each faunal group and species are also reported.

Taxon	DIS species	Abundance (N/min haul)	Biomass (g/min haul)	%N	%B	FO
Asteroidea	*A. irregularis*	5.4 ± 1.8	18.7 ± 6.1	6.7	2.5	100
Bivalvia	*A. kagoshimensis*	3.1 ± 1.9	24.9 ± 7.2	3.8	3.3	89.0
	A. tuberculata	3.2 ± 0.8	60.2 ± 20.4	4.0	8.0	100.0
	D. lupinus	0.5 ± 0.4	< 0.1 ± 0.1	0.6	< 0.1	33.0
	D. semistriatus	1.7 ± 0.6	0.4 ± 0.1	2.1	0.1	89.0
	M. stultorum	10.1 ± 2.4	75.8 ± 16.9	12.5	10.1	100.0
	O. edulis	< 0.1 ± 0.1	0.3 ± 0.2	< 0.1	< 0.1	22.0
	P. aureus	0.3 ± 0.1	0.8 ± 0.4	0.4	0.1	67.0
	P. planata	< 0.1 ± 0.1	0.4 ± 0.4	< 0.1	0.1	11.0
Mean		19 ± 3.3	163 ± 28.3	23.4	21.6	63.9
Echinoidea	*E. cordatum*	10.3 ± 4.5	97.6 ± 43.6	12.7	13.0	89.0
Elasmobranchii	*Raja* sp.	< 0.1 ± 0.1	0.3 ± 0.3	< 0.1	< 0.1	11.0
Gastropoda	*B. brandaris*	0.1 ± < 0.1	1.8 ± 0.8	0.1	0.2	44.0
	N. josephinia	0.5 ± 0.2	3.9 ± 1.5	0.6	0.5	67.0
	N. stercusmuscarum	0.4 ± 0.3	3 ± 2.1	0.5	0.4	44.0
	P. aperta	0.1 ± 0.1	0.2 ± 0.2	0.1	< 0.1	11.0
	T. mutabilis	0.2 ± 0.2	0.6 ± 0.5	0.2	0.1	22.0
Mean		1.3 ± 0.6	9.6 ± 3.1	1.6	1.3	37.6
Malacostraca	*D. pugilator*	1.1 ± 0.7	3.8 ± 2.5	1.4	0.5	78.0
	I. nucleus	0.2 ± 0.2	0.5 ± 0.5	0.2	<0.1	11.0
	L. vernalis	43.8 ± 9	460 ± 86.3	54.1	61.1	100.0
Mean		45.1 ± 9.2	464 ± 87.2	55.6	61.6	63.0
Palaeonemertea	Palaeonemertea	< 0.1 ± 0.1	0.1 ± 0.1	< 0.1	< 0.1	11.0

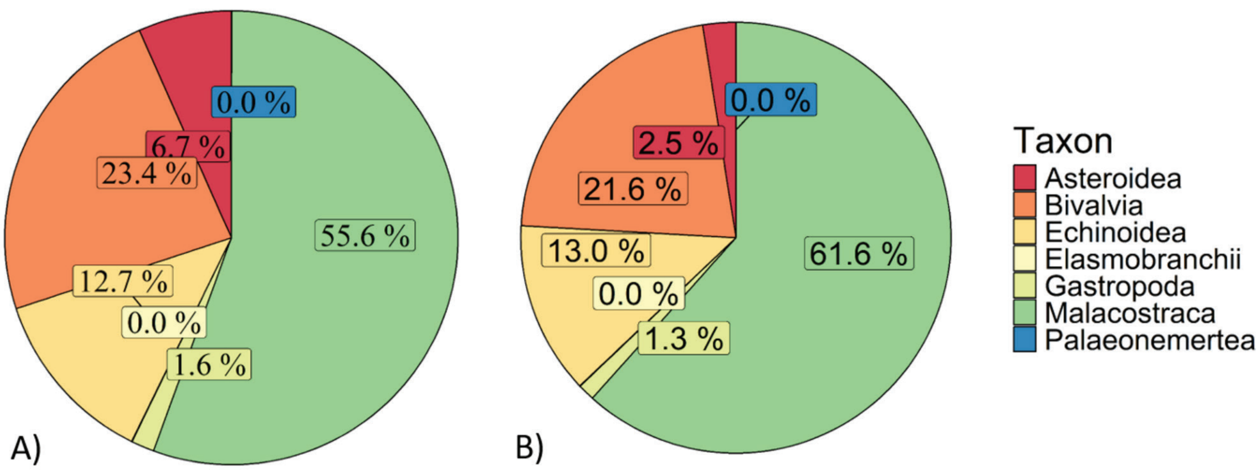

Fig. 2: Mean standardized percentages in *a)* number and *b)* weight of the faunal groups collected as non-target and discarded in the striped venus clam fishery.

Table 3. DIS fractions as a function of haul duration (3, 6 and 9 min) and damage level (D_0-D_3). In brackets, the 95% CIs. The last column shows the *p* values relative to fractions comparison for each row.

Damage class	3 min	6 min	9 min	p-value
D_0	0.627 (0.594, 0.660)	0.600 (0.558, 0.637)	0.548 (0.511, 0.584)	0.006
D_1	0.265 (0.236, 0.296)	0.181 (0.152, 0.214)	0.180 (0.153, 0.210)	<0.001
D_2	0.023 (0.015, 0.036)	0.024 (0.014, 0.039)	0.053 (0.039, 0.072)	0.001
D_3	0.085 (0.067, 0.106)	0.198 (0.168, 0.232)	0.219 (0.190, 0.251)	<0.001

for each discarded species and there were only 4 ubiquitous species (i.e. *A. tuberculata*, *M. stultorum*, *L. vernalis* and *A. irregularis*) and others mainly common ones (i.e. *D. semistriatus*, *Anadara kagoshimensis*, *Diogenes pugilator*, and *E. cordatum*); despite the fact that each of them had a different weight in determining the mean abundance and biomass fraction (Table 2).

ANOSIM analysis carried out on abundance data showed no significant differences between hauls (R = -0.096, *p* = 0.96); see Fig. 3, indicating that the macro-benthic community structure was similar between hauls.

Of the 9 hauls carried out, all showed signs of moderately disturbed macro-benthic communities as shown from ABC plots in which the biomass is constantly slightly above the abundance curve, intersecting only at higher species ranks (Supplementary Fig. S1, Fig. 4). The moderate disturb is also confirmed by the Warwick Statistics (W), as the index never goes into the negative field but does not differ much from zero (Supplementary Fig. S2).

Discard damage and mortality rate

Overall, a significant difference ($p \leq 0.05$) was found in damage rates with haul durations when the total DIS fraction was considered (Table 3). The fraction of individuals in damage classes D_0 and D_1 decreased following increasing haul time, whereas the fraction of individuals in D_2 and D_3 increased following higher haul durations.

On the other hand, testing for differences in damage rate between haul durations stratified at taxon or species level showed very few significant differences: at taxon level, only two cases (Bivalvia for damage level D_0 and D_3 without showing a clear trend) out of 24, and at species level no case out of 52 (Supplementary Table S2, Table S3). Also, the total mortality rate of DIS did not show any significant difference with haul durations: see Tukey HSD *post hoc* test in Table 4. Given the almost total absence of a particular trend in damage and mortality rates for the haul times tested in the present study at taxon and species level, in the rest of the paper the DIS fractions will be standardized - both in abundance and biomass -

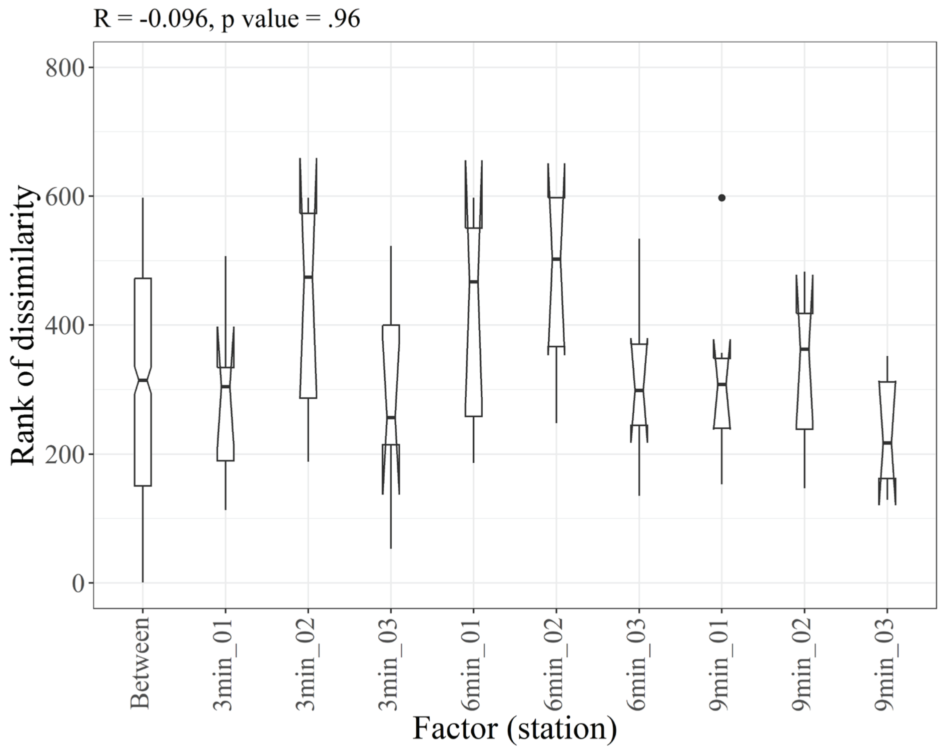

Fig. 3: ANOSIM plot representing the benthic community structure in each haul of the striped venus clam fishery in San Benedetto Maritime Districts: the ranks of distances among sample units from different groups ('Between') and among sample units within the haul groups.

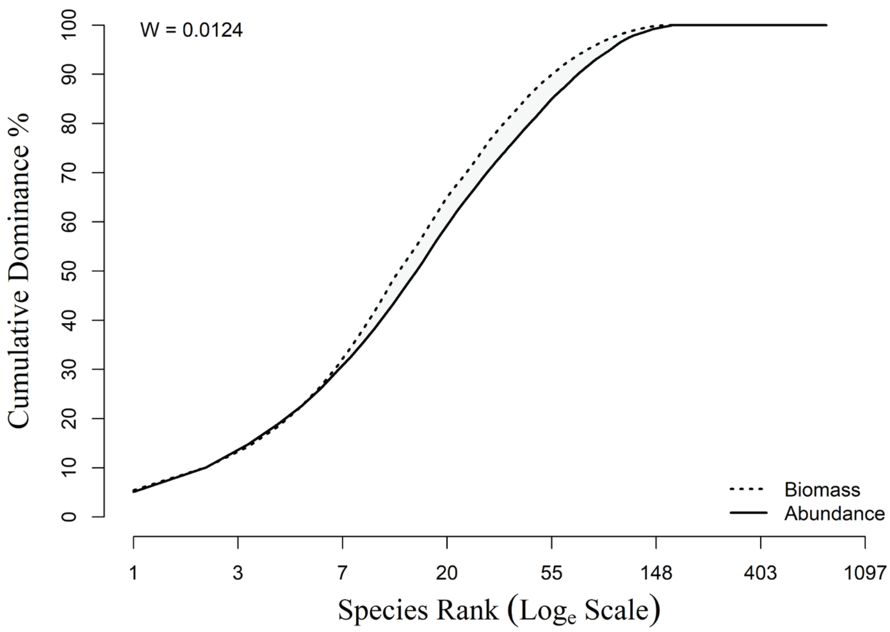

Fig. 4: Overall ABC plots generated from the combination of mean abundance (continue line) and biomass (dotted line) data relatively to the 9 hauls.

Table 4. Results of the Tukey HSD post hoc test for the effects of haul durations (3, 6 and 9 min) on the overall mortality rate of the discard fraction (DIS).

Tukey HSD test: Mortality rate				
Haul duration	diff	lwr	upr	p adj
6 min *vs* 3 min	-0.075	-0.346	0.195	0.778
9 min *vs* 3 min	-0.068	-0.325	0.188	0.796
9 min *vs* 6 min	0.007	-0.259	0.274	0.998

per min/haul to describe the overall damage and mortality rates induced by hydraulic dredging.

Overall, 61.0% of the individuals were undamaged, whereas 16.1%, 3.7% and 19.2% displayed slight, intermediate and severe damage, respectively. Intact individuals in damage class D_0 were dominated by Malacostraca, almost totally represented by the grey swimming crab *L. vernalis* (57.7% and 64.7% of total abundance and biomass, respectively) and Bivalvia (29.5% and 28.4%), followed by less dominant species or taxa such as the sea star *A. irregularis* (7.3% and 2.5%), Gastropoda (2.4% and 1.8%), the sea urchin *E. cordatum* (0.9% and 1.7%), Elasmobranchii and Palaeonemertea (≤ 0.1% and ≤ 0.1%). Among Bivalvia, worth noting is *A. kagoshimensis*, where 100% of collected individuals were classified as intact, although frequent signs of previous damage, subsequently repaired, were detectable on the shells. Slightly damaged individuals in class D_1 were dominated exclusively by the grey swimming crab *L. vernalis* (85.5% and 92.4%), despite a minor dominance by the sea star *A. irregularis* (9.3% and 3.1%); Bivalvia (4.0% and 3.6%) and Gastropoda (1.0% and 0.8%) were also present. Within this damage, the bivalve *Ostrea edulis* was the species mainly damaged (50% of total collected individuals), showing chipped edges of the shell, whereas Gastropoda *Bolinus brandaris* (40%) and *Neverita josephinia* (9.1%) showed major damage with chipped edges of the shell. Intermediately damaged individuals in class D_2 were dominated by the sea urchin *E. cordatum* (43.2% and 49.9% of total abundance and biomass, respectively), the grey swimming crab *L. vernalis* and the nut crab *Ilia nucleus* (42.0% and 40.4%), followed by the bivalves *M. stultorum* and *A. tuberculata* (12.5% and 8.9%) and the sea star *A. irregularis* (2.3% and 0.8%). For *I. nucleus*, only one individual was recorded on the whole sampling, showing major carapace cracks and all legs missing. Severely damaged individuals in class D_3 were dominated by the sea urchin *E. cordatum* (61.7% and 65.6% of total abundance and biomass, respectively), Bivalvia (26.1% and 21.2%) – with *M. stultorum* and *P. aureus* being the mainly damaged species within this class - and the grey swimming crab *L. vernalis* (9.8% and 11.1%), whereas the sea star *A. irregularis* contributed marginally (2.5% and 2.1%) (see Fig. 5, Fig. 6 and Supplementary Table

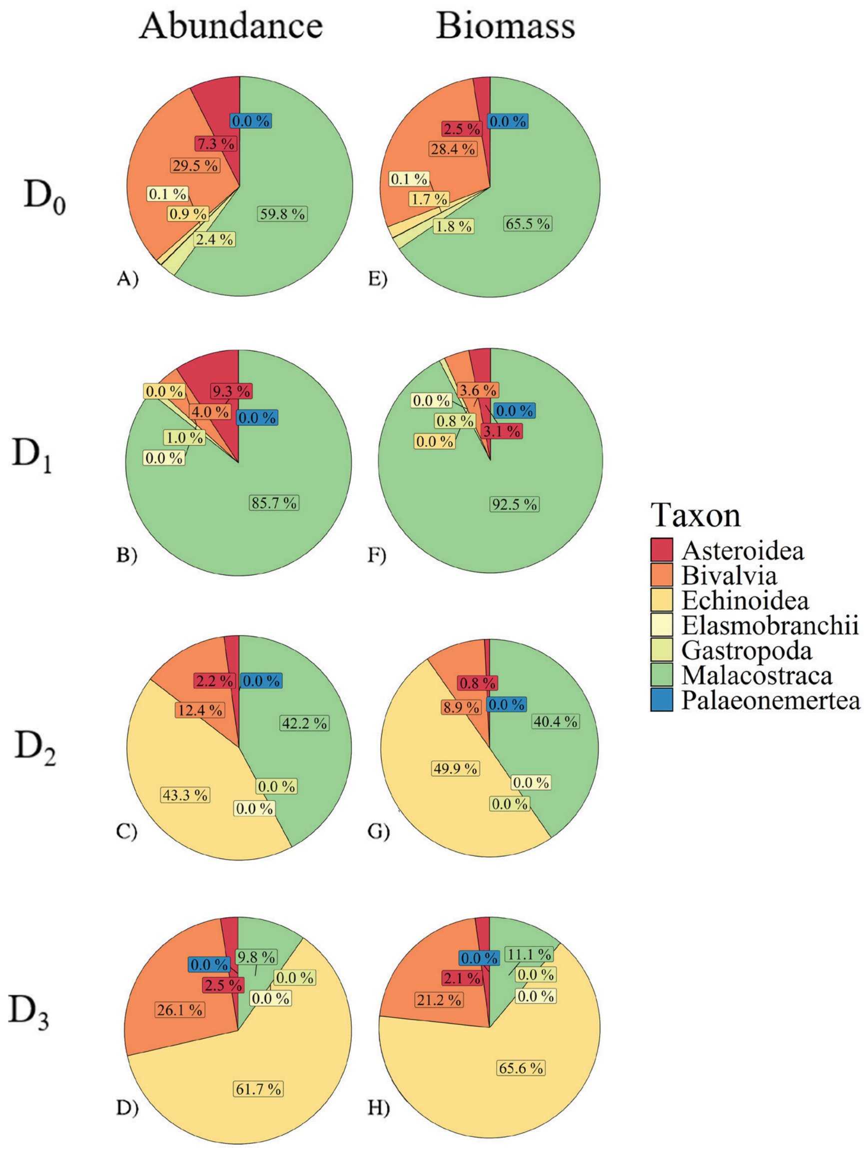

Fig. 5: Overall standardized percentage of taxa displaying different damage levels (from D0 to D3 along the column) for all non-target species bycaught as discard in the striped venus clam fishery in terms of abundance/min haul (a-d) and biomass/min haul (e-h).

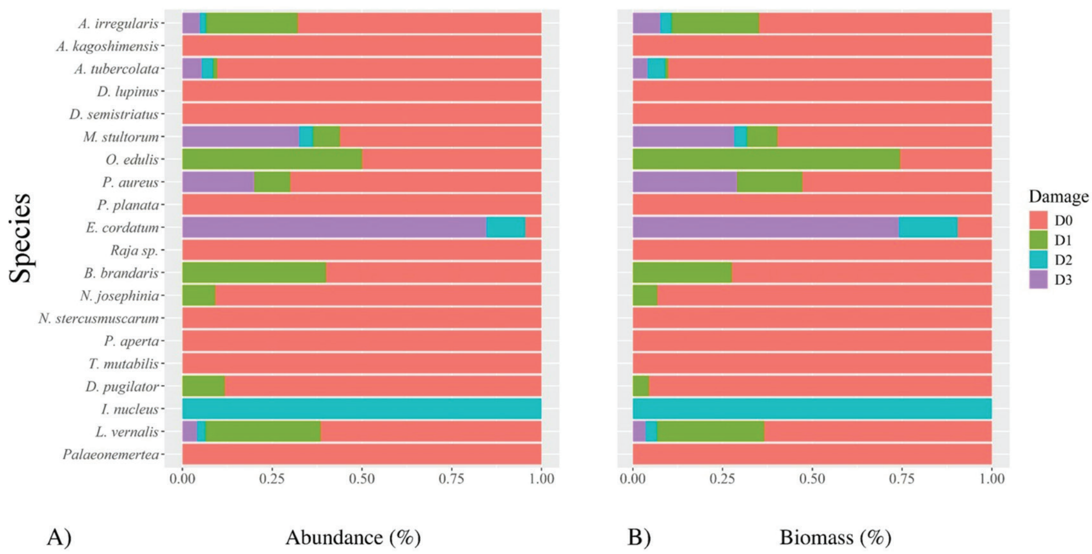

Fig. 6: Overall standardized percentages in terms of a) number and b) weight of each non-target discarded species collected in the striped venus clam fishery in relation to damage level (D0-D3).

S3, Table S4). These results show that soft-shelled or soft-body species (i.e. *E. cordatum*, *I. nucleus*, *M. stultorum* and *P. aureus*) were those most affected by the harvesting process, whereas thick-shelled or thick-body species suffered less damage. The greatest sensitivity to the catch is shown by the sea urchin *E. cordatum*, where 84.6% of total individuals caught were completely smashed, while 10.9% suffered minor but unrepairable cracks. The second most damaged species was the soft-shelled *M. stultorum*, followed by *P. aureus* with 32.5% and 20.0% of total individuals caught completely crushed, respectively (Fig. 6 and Supplementary Table S4).

Overall, the mortality rate was 22.9% for all discarded individuals. The sea urchin *E. cordatum* was extremely sensitive to dredging, with the highest mortality rate of 96.0%, although it belongs to the third most represented taxon in DIS. Bivalvia and Malacostraca (*L. vernalis*) – representing the second and the first most abundant taxa in DIS, respectively – show a mortality rate of 23.0% and 6.5%. Among the less abundant discarded species, instead, the sea star *A. irregularis* had a mortality rate of 7.0%.

Discussion

Discard analysis has raised much attention in the recent years, since the issue has been pointed out as an important aspect for fisheries management, especially after the establishment of the ecosystem approach to fisheries (FAO, 2003; Garcia *et al.*, 2003; Pikitch *et al.*, 2004), and the implementation of diverse European directives and regulations (e.g. Commission Regulation 1581/2004, Regulation (EC) 1380/2013). However, the assessment of bycatch/discard is a critical issue for evaluating the sustainability of any fishery. Studies aimed at assessing the impact of dredging (hydraulic or mechanized) on macro-benthic communities structure are still few (Morello *et al.*, 2005b; Constantino *et al.*, 2009; Vasapollo *et al.*, 2020; Baeta *et al.*, 2021a) because data before the impact is often lacking, and the same holds true of the time series on the composition of discards to detect patterns of change of faunal communities. Nevertheless, some studies have evaluated the discard catch composition (Dalgıç & Ceylan, 2012; *Başçinar et al.*, 2020; Urra *et al.*, 2021b) and, especially along Spanish and Portuguese coasts, also started to focus on the damage exerted by dredging on non-target species and the consequent mortality derived (Gaspar *et al.*, 2002, 2003b,a; Urra *et al.*, 2017, 2021a; Anjos *et al.*, 2018; Baeta *et al.*, 2021a).

In this study, the mean fraction of non-target species rejected to the sea (DIS) was extremely low, 4.4% of the total weight caught, indicating that the area was mostly dominated by the target species forming a "*facies* à *C. gallina*" (Pérès & Picard, 1964). Indeed, clam dredging generally occurs in areas where the target species is the dominant one in macro-benthic communities, and, therefore, the proportion of discard is often relatively low (Butcher *et al.*, 1981). However, if we include among discards even the striped venus clam USZ fraction, in the study a high discard rate was found, indicating the presence of abundant resource promoting the maintenance of clam population on this fishing ground at the time of sampling. Given the different haul durations herein considered, USZ significantly increased with haul time but was not the same for COM and DIS, probably because of clogging of the dredge (Petetta *et al.*, 2021). Different authors reported variable percentages of discards in bivalves' dredge fishery depending on the gear, fishing grounds and seasonality, ranging from 6.3% to 82.0% (Morello *et al.*, 2005b; Anjos *et al.*, 2018; Baeta *et al.*, 2021a). Moreover, in accordance with our findings, the undersized commercial species, regardless of the time of sampling, frequently accounted for more than half of the discarded fraction. For example, in the striped venus clam fishery of the Black Sea, Dalgıç & Ceylan (2012) found that 36.0% of the catch was unwanted (19.0% undersized clams and 17.0% non-target species), whereas in the wedge clam fisheries of the Alboran Sea (Urra *et al.*, 2017, 2021a) it was found that 42.0% (25.0% undersized clams and 17.0% non-target species) and 22.7% (13.2% undersized clams and 9.5% non-target species) of the catch was unwanted in 2013-2014 and 2018, respectively. On the other hand, other studies recorded considerable amount of discards in the bivalve dredge fisheries along the Algarve coast, even exceeding the catch of the target species at some times of the year (Gaspar & Chícharo, 2007).

Many factors can influence the amount of discard, one of which is seasonality. Indeed, seasonal trends have been observed in the discards composition, abundance and biomass related to abiotic and biotic factors (Gaspar & Chícharo, 2007; Dalgıç & Ceylan, 2012; Urra *et al.*, 2013, 2021b; Carlucci *et al.*, 2024). In this study, carried out in summer, the discarded fraction of non-target species was very low, whereas Başçinar *et al.* (2020) found higher abundances in summer followed by the spring season, Urra *et al.* (2021b) in winter and Dalgıç & Ceylan (2012) in autumn. These peculiar patterns can be explained by different environmental conditions as to seasons and population dynamics of the benthic species related to their biology and ecology (i.e. reproductive or feeding strategies). Moreover, where fishing intensity is higher, discards could be lower as a direct result of large-body and slow-growing species removal (Urra *et al.*, 2021b), even if the non-homogenous distribution of a species within a fishing ground could also explain the variable amount of discards (Pranovi *et al.*, 2001).

The ANOSIM revealed a similar benthic community structure between hauls, possibly because of the same bathymetry at which hauls were conducted. Indeed, great variability in the catch composition of the striped venus clam fishery was found at different bathymetries in the western Adriatic Sea, near the area of our sampling, revealing a clear segregation of the benthic community according to depth (Morello *et al.*, 2005a). On the other hand, in the South Adriatic it was found that during summer macro-benthic assemblages showed a high overlap over different areas characterized by different bathymetries, although in winter assemblages they were well-distinct in each area (Carlucci *et al.*, 2024). However, the faunal composition documented here is quite similar to that observed in discards close to Mediterranean areas (Morello *et al.*, 2005a,b; Anjos *et al.*, 2018; Urra *et al.*, 2021a; Carlucci *et al.*, 2024), although the total number of species detected was much lower, indicating an important difference in species richness, potentially related to the abovementioned factors.

According to what was observed by Malaquias *et al.* (2006) along the continental shelf (where also dredges operate) and slope, crabs were the most represented faunal group in terms of abundance and biomass, while mollusks were the most diversified one, despite the fishing gear employed and the sampling area investigated were not the same as those of the present study. The findings herein reported show that DIS composition mainly consisted of benthic species with large dimensions and morphological features that prevented their passage through the rods of the gear, such as larger bivalves, crabs and heart urchins, although representatives of a number of small-bodied species were also retained since, as reported by Petetta *et al.* (2021), within a short time the dredge fills up preventing the passage of specimens regardless of their size. As stated by Kaiser *et al.* (2000), the heavily fished areas are dominated by higher abundances of smaller bodied organisms, whereas the less intensely fished areas are dominated by fewer, larger-bodied biota. The ABC plots together with the W revealed moderately disturbed macro-benthic communities within the investigated area, as also indirectly confirmed by the moderate high abundances of large and/or soft-bodied individuals composing discards, particularly of *L. vernalis, E. cordatum* and *M. stultorum*, which accounted for much of the total number and weight of discards. Indeed, samples were collected close to the 0.3 NM, the limit within which clam fishing is banned, so even if fishing is interdicted in this area, GPS data confirms that it is sometimes illegally dredged (*unpublished data*), explaining the level of disturbance herein investigated. In the smooth clam fishery, Baeta *et al.* (2021b) observed that the abundance of *E. cordatum* was higher in unexploited bottoms after 5 years of fishing closure and species with fragile shells like *M. stultorum* also appeared on those grounds in the absence of fishing activity. By comparing the macro-benthic species composition between control and dredged plots before and after a fishing disturbance in a fishing area very close to the one considered in the present study, (Maritime District of Ancona, Mid-western Adriatic Sea), Morello *et al.* (2005b) found that the swimming crab *L. vernalis* was associated with control sites. Moreover, the scavenging gastropod *Tritia mutabilis* had a strong difference in its biomass, albeit not significant, between dredged and control plots, the higher being in dredged ones, indicating that the ground we explored was not previously intensively fished, since its frequency of occurrence herein detected was quite low (22.0%). Therefore, other findings compared to the ones herein reported help the present authors to support the statement on assessing the moderate fishing intensity previously experienced by the grounds where the sampling activity was conducted.

Damage rates induced by dredging activity on target or macro-benthic species are attributable to different factors (e.g. clam dredge technical design, fishing operation, intensity and frequency of fishing activity, catch efficiency, local environmental conditions, haul time, grain size, depth, quantity of the catch, and species behaviour) (Gaspar & Chícharo, 2007). In the present study, it was found that total DIS was damaged the most (damage classes D_2 and D_3 mainly represented) with increasing haul duration, while intact and slightly damaged individuals decreased consecutively, although such differences were no longer detectable when testing for differences in damage rate between haul durations stratifying at taxon or species level. Overall, a large fraction of the total discarded non-target species was damaged (39.0%), of which more than half suffered higher damage levels (3.7% intermediate and 19. 2% severe damage, respectively). Similar estimates of the damaged discarded total fraction (about 40.0%) were found for the smooth clam fishery by Baeta *et al.* (2021b), albeit with different proportions between the intermediately and severely damaged fractions (*ca.* 14.0% and 26.0%, respectively). Lower estimates were instead found in other studies accounting for different clam fishery activities. For instance, in the western Mediterranean Sea the fisheries targeting *C. gallina* showed 4.5% and 11.0% of discarded individuals with intermediate and severe damage, respectively, whereas in the one targeting *D. trunculus*, 15.0% and 12.0% of discards exhibited intermediate and severe damage (Urra *et al.*, 2017, 2019). These notable differences in the proportion of discards suffering damage may be the result of the abovementioned different biotic, abiotic and technical factors.

In the Mediterranean Sea, clam dredging fisheries frequently occur on shallow coastal areas, which are high-energy habitats, and benthic communities seem to be well-adapted to short and medium-term perturbations showing a high level of resilience (Tuck *et al.*, 2000; Constantino *et al.*, 2009; Ragnarsson *et al.*, 2015; Vasapollo *et al.*, 2020). However, it is also expected that fragile, near surface dwelling and larger species are impacted more by fishing activity. We found that soft-bodied or soft-shelled species (i.e. *E. cordatum, I. nucleus, M. stultorum, P. aureus*) were the most sensitive to clams dredging, as widely reported by other authors (e.g. Hall-Spencer & Moore, 2000; Pranovi *et al.*, 2001; Urra *et al.*, 2017, 2021b). *E. cordatum*, whose exoskeleton is formed by very thin plates fused together, was the most affected species experiencing the highest percentages in severe damage 85.0% and mortality rate 96%, in agreement with other authors who reported it to be the most vulnerable species to different types of clam dredging (Tuck *et al.*, 2000; Urra *et al.*, 2017; Baeta *et al.*, 2021b). Nonetheless, lower damage and mortality rates (< 70% and < 30%, respectively) were also reported for the species (Tuck *et al.*, 2000; Hauton *et al.*, 2003; Anjos *et al.*, 2018). The thin shelled *M. stultorum* was the second most affected species suffering severe damage > 32.0% and mortality rate > 36.0%, even though higher percentages of damage and mortality have been detected for the genus *Mactra* (> 75.0% and 60.0%, respectively) (Anjos *et al.,* 2018). The bivalve *P. aureus* was the third most impacted species, although it showed moderately severe damage and mortality (20.0%); its vulnerability was attributable to the fragile thin shell (Morello *et al.*, 2005b). The only individual of *I. nucleus* found suffered intermediate damage and was regarded as dead; similarly Baeta *et al.* (2021b) found that it suffered 50.0% severe damage, indicating a high probability of being cracked due to its thin carapace. On the other hand, we found that thickened shells or individuals with strong protections were less sensitive to dredging. Among the most representative thick-shelled bivalves, *A. kagoshimensis* suffered no damage, whereas *A. tuberculata* suffered minor, intermediate and severe damage, but with a low mortality rate (<9.0%), thanks to their shell thickness (Urra *et al.*, 2017). Also, gastropods and the hermit crab *D. pugilator* showed only slight damage with no mortality rate thanks to their robust, thick shells unlikely to break, as similarly previously reported by different authors (Bergmann *et al.*, 2001; Pranovi *et al.*, 2001; Gaspar *et al.*, 2002; Anjos *et al.*, 2018). The swimming crab *L. vernalis* occurred in high abundances and mainly suffered slight damage (32.0%) and a mortality rate of 6.5%, in line with the other study where damage ranged between 25.0 and 39.0% and the mortality rate between 0.0 and 14.0% (Anjos *et al.*, 2018). The mobile species *A. irregularis* mainly suffered minor damage (ca. 26.0%) and a low mortality rate (ca. 7.0%), although it has been reported as a species that can suffer highly severe damage, since it is in general widely distributed and not restricted to a certain sediment type, being caught by different trawling activity increasing the likelihood of damage (Bergmann *et al.*, 2001; Pranovi *et al.*, 2001). Our results are in line with the slight damage detected by Pranovi *et al.* (2001) on *A. irregularis* and *L. vernalis* in the flatfish fishery, whereas they were found to suffer major severe injuries in the scallop fishery, probably because of the large amount of hard shells harvested, which macerate the catch during towing and hauling.

The estimated direct mortality of the total discarded fraction was moderately high (*ca.* 23.0%), regardless of the fact that it might have been underestimated, as high levels of mortality can occur independently of the level of damage (Bergmann & Moore, 2001a,b). Unobserved post-fishing mortality can occur in both damaged and undamaged individuals depending on dredge-induced stress, air exposure, the time needed to reach the sea bottom and rebury (for infauna) or resume normal activity (epifauna), which can affect predation (Chícharo *et al.*, 2002; Maguire *et al.*, 2002; Gaspar *et al.*, 2003a; Broadhurst *et al.*, 2006; Gaspar & Chícharo, 2007). In the venus clam fishery, the catch is rapidly sorted on the deck and non-target and undersized target species are returned to the sea near the natural beds in a short time, probably without affecting mortality too much. However, predators and scavengers have been observed to aggregate very quickly along the dredge tracks, preying not only on damaged organisms but also on undamaged ones before they have had the opportunity to rebury (Hall-Spencer & Moore, 2000). This aggregation can last from just a few minutes (Gaspar *et al.*, 2003b) to a few days (Jenkins *et al.*, 2004). All these factors accounting for indirect-post fishing mortality should be taken into consideration for the calculation of more real mortality estimates, and survival experiments should thus be carried out, especially directly at sea without excluding predation. At present, only a few studies carried out survival experiments on discarded macro-benthic species returned to the sea after fishing operations. For instance, Anjos *et al.* (2018) conducted survival experiments on containment facilities, finding diverse vulnerability of taxa to survivorship, confirming the influence of damage score on mortality rate, whereas Gaspar *et al.* (2003b) assessed survivorship directly at sea on dislodged individuals according to damage and gear type. A future challenge is to increase the number of studies aimed at gaining information on damage and mortality rates induced also on uncaught dislodged individuals left on the dredge path. This is so to have a full view of the effects caused by dredging activity. In addition, further studies aimed at investigating the effects of dredging on benthic communities, both on a spatial and a temporal scale, are needed for the future, in order to adopt suitable management plans and actions with the view to achieving a responsible and sustainable fishing activity.

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Author contributions: GB1, AL and MV conceptualized the work together. GB1 wrote the manuscript and SG, MV and AL revised it. GB1 and GB2 collected the samples at sea, while GB1 processed the samples in the laboratory. SG performed statistical analyses and data visualization. AL was the scientific responsible for the study. All the authors contributed to the article and approved the submitted version. **Data Availability Statement:** The data supporting the findings of this study is available from the Italian Ministry of Agricultural, Food and Forestry Policies (MASAF). **Conflict of Interest Statement:** The authors have no conflicts of interest to declare. **Ethics Statement:** All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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Supplementary Material

The following supplementary material is available for this article:

Table S1. Details of the catch for each haul. NSV: not-sieved, COM: commercial, DIS: discard, USZ: undersized, DR: discard ratio.

Fig. S1: ABC plots generated from the combination of abundance (continue lines) and biomass (dotted lines) data for each haul.

Fig. S2: W plot of the hauls. The index is never negative and does not differ much from zero, confirming the indications by the ABC plots of a moderate disturbance.

Table S2. Table of proportions (with 95% CIs) and p-value showing differences in damage rate between haul durations stratified at taxon level. NA: not available (the software could not calculate the p-value); "-": 0/0.

Table S3. Table of proportions (with 95% CIs) and p-value showing differences in damage rate between haul durations stratified at species level. NA: not available (the software could not calculate the p-value); "-": 0/0.

Table S4. Overall standardized percentages in terms of number and weight of each non-target discarded taxon and species collected in the striped venus clam fishery in relation to damage level (D_0-D_3).