

## Mediterranean Marine Science

Vol 22, No 1 (2021)

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doi: [10.12681/mms.24973](https://doi.org/10.12681/mms.24973)

#### To cite this article:

EZGETA -BALIĆ, D., VRGOČ, N., ISAJLOVIĆ, I., MEDVEŠEK, D., VUJEVIĆ, A., DESPALATOVIĆ, M., & CVITKOVIĆ, I. (2021). Comparison of beam trawl catch, by-catch and discard in fishing and non-fishing areas – a case study from the northern Adriatic Sea. *Mediterranean Marine Science*, 22(1), 108–120. <https://doi.org/10.12681/mms.24973>

## Comparison of beam trawl catch, by-catch and discard in fishing and non-fishing areas – a case study from the northern Adriatic Sea

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Contributing Editor: Stelios SOMARAKIS

Received: 6 November 2021; Accepted: 15 January 2021; Published online: 12 February 2021

### Abstract

Beam trawl fishery is highly important in the Croatian part of the northern Adriatic wherein 116 vessels have a licence for this type of fishing gear. A sharp decrease in the beam trawl catch observed since 2015 has raised concern about not only socio-economic issues but also ecological issues and the effect that beam trawl fisheries have had on exploited stocks. Besides the effect that beam trawl fisheries can have on targeted economically important species, intensive dredging can cause long-term changes in the benthic community. Therefore, this study aimed to detect the effect that this type of fishing gear has on target and by-catch species. Furthermore, survey data were compared with the official beam trawl fishery data gathered through Vessel Monitoring System data together with fishermen's logbooks. Our research targeted two adjacent areas: an area where beam trawl fishing is allowed and an area where it is forbidden. The results demonstrate that the commercially important catch represented a minor share of the total beam trawl catch in both survey areas, while discard made up more than 93% of the total catch. The main beam trawl commercially important species in the Croatian part of the northern Adriatic Sea was *Pecten jacobaeus*, followed by *Solea solea* and *Ostrea edulis*. Our results suggest that beam trawl fisheries mostly affect target bivalve species and some non-commercial benthic species (e.g. sponges). The differences recorded between areas could suggest that beam trawl fisheries cause changes mostly in the *P. jacobaeus* population.

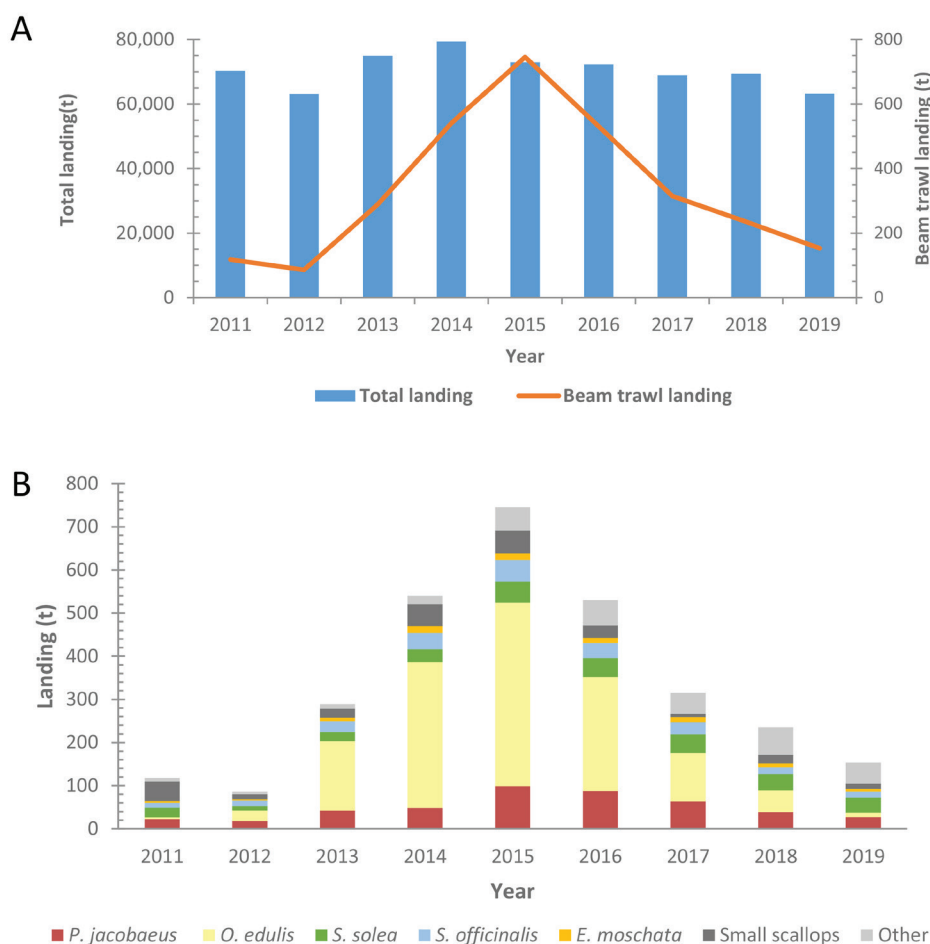
**Keywords:** Mediterranean scallop; European flat oyster; common sole; VMS; logbooks; population structure; benthic organisms; fishing effort.

### Introduction

Considering the high percentage of stocks fished at unsustainable levels in the Mediterranean area concern about the sustainability of the current level of fishery exportation is justified (Colloca *et al.*, 2017). Marine resources, together with intensive fishing (Corrales *et al.*, 2018), are constantly exposed to different threats such as habitat degradation (Villéger *et al.*, 2010), increased pollution (Compa *et al.*, 2019), climate-driven change (Corrales *et al.*, 2018) and the introduction of non-native species (Katsanevakis *et al.*, 2016). High exploitation has caused a decrease in the abundance of target species as well as changes in their population structure (Jennings *et al.*, 1999; Myers *et al.*, 1996). Population structure changes are expressed as a decrease in the mean maximum size/age and size at maturity (Jennings *et al.*, 1999). Furthermore, overexploitation of target species, especially top-predators, modifies the food web structure and

consequently the structure of the entire ecosystem (Maureaud *et al.*, 2017). Intensive fishing activity, besides the target species also affects by-catch species. Mobile fishing gear, such as beam trawls, cause damage and changes to the benthic community (Pranovi *et al.*, 2000, 2001).

In the Adriatic Sea, fishery resources are shared between Albania, Montenegro, Croatia, Slovenia and Italy. While the total capture production of Albania, Montenegro and Slovenia together is less than 10 000 tonnes (instat.gov.al; www.monstat.org; ec.europa.eu/eurostat), the capture production of Croatia and Italy is several-fold higher. According to the Croatian Directorate of Fisheries, capture production in the Croatian part of the Adriatic Sea in the last few years was ~70 000 tonnes per year (Fig. 1A) while Italian capture production was much higher at ~190 000 tonnes per year (ec.europa.eu/eurostat). Although according to national statistic beam trawl catch contributes relatively little to total production in Croatia (<1%), it is important in the northern Adriatic



**Fig. 1:** Official statistics on annual capture production and annual beam trawl landing in Croatia (A) and landing of the main commercial species from beam trawl fisheries (B) (Croatian Directorate of Fisheries).

(Croatia) area wherein 116 vessels have a licence for this type of fishing gear but not all are active. In 2017, in total 68 vessels were active while a slight decrease of the active vessels was recorded in 2018 and 2019 when 60 and 53 vessels were active, respectively. Among active vessels in 2019, majority of 91 % belongs to the smaller vessels: vessels smaller than 12 m made up 40% while vessels between 12 and 15 m made up 51%. Larger vessels made up only 9% of the active beam trawl vessel fleet: vessels between 15 and 18 m made up 8%, while those larger than 24 m contributed only 1%. Those vessels in average had  $50.6 \pm 47.7$  working days, while the recorded maximum was 176 working days. According to the national statistic daily landing of beam trawl fleet in 2019 ranged from 1.2 to 889.0 kg with an average of  $65.2 \pm 34.2$  kg. Most of beam trawl fleet, depending on the catch profitability, switch to bottom trawl fishing during a certain period of the year.

The sharp decrease in the beam trawl catch observed since 2015 has raised concern about not only socio-economic issues but also ecological issues and the effect that beam trawling has had on exploited stocks. In the Italian and Croatian parts of the Adriatic Sea, different types of beam trawls are used. In the Italian region of the Adriatic Sea, towed gear called ‘rapido’ (classified in the category ‘bottom trawl’) is used for scallop (*Pecten jacobaeus* and

*Aequipecten opercularis*) fishing in the sandy offshore area and flatfish (*Solea* spp., *Platichthys flesus*, *Psetta maxima* and *Scophthalmus rhombus*) fishing in the muddy inshore areas (Pranovi *et al.*, 2001). According to Croatian legislation, bivalves are target species in beam trawl fisheries (gear called ‘rampon’) (Official Gazette 12/2016; Official Gazette 48/2015), mostly two species: the Mediterranean scallop *Pecten jacobaeus* and European flat oyster *Ostrea edulis* (Fig. 1B). However, three other commercially important species, the common sole *Solea solea*, European common cuttlefish *Sepia officinalis* and musky octopus *Eledone moschata*, are frequently present in the beam trawl as by-catch. Furthermore, recently, species that were previously considered as discard have become commercially valuable. Those species include the small scallops *Flexopecten glaber*, *Aequipecten opercularis* and *Mimachlamys varia*, and muricid gastropod species *Hexaplex trunculus* and *Bolinus brandaris*. Besides the effect on target and commercially important by-catch species, mobile fishing gear such as beam trawls causes damage to macrobenthic species (Pranovi *et al.*, 2000, 2001). Intensive dredging can cause long-term changes in the benthic community (e.g. Collie *et al.*, 1997).

Although some beam trawl studies have been performed in the Adriatic Sea (Hall-Spencer *et al.*, 1999; Pranovi *et al.*, 2000, 2001; Scarcella *et al.*, 2007), they

were focused on the western Adriatic, while there are no data about the impact of beam trawling on the marine resources in the eastern part of the Adriatic Sea. This study aimed to detect the effect that this type of fishing gear has on the most exploited species in the northern Adriatic Sea. We targeted two adjacent areas, within same depth stratum (20–40 m) but different fishing regulations: an area where beam trawl fishing is allowed and an area where it is forbidden. In both regions, other types of fishing gear are allowed, including bottom trawl, trammel-net and gill-net fisheries, and the synergistic effect of those types of fishing gears on exploited species is discussed. Furthermore, this study provides valuable information on the beam trawl fishing effort and landings in the northern Adriatic Sea and compare national statistics with the data obtained during the scientific surveys.

## Material and Methods

### Study area

The study was performed in the northern Adriatic Sea in the fishing zone A (Fig. 2). Although other fishing gears (e.g. bottom trawl, trammel-net, gill-net fisheries etc.) are allowed in the entire zone, beam trawl fishery is allowed only in one part of this zone (Official Gazette 12/2016; Official Gazette 48/2015). The survey was conducted in the beam trawl fishing area during October 2017, and in the beam trawl non-fishing area during October 2018. Investigated areas are stretched along the west coast of Istria. Trawling was undertaken by a commercial fishing vessel towing two beam trawls (frame dimensions 180 cm × 50 cm, equipped with a toothed bar with teeth 9 cm apart and 10 cm long). The beam trawl net is fitted out with a 4 m long diamond mesh with 40 mm knot-to-knot mesh size (80 mm stretched mesh size). Table 1 contains the main information about the performed tows. Tow duration varied depending on the amount of catch, technical

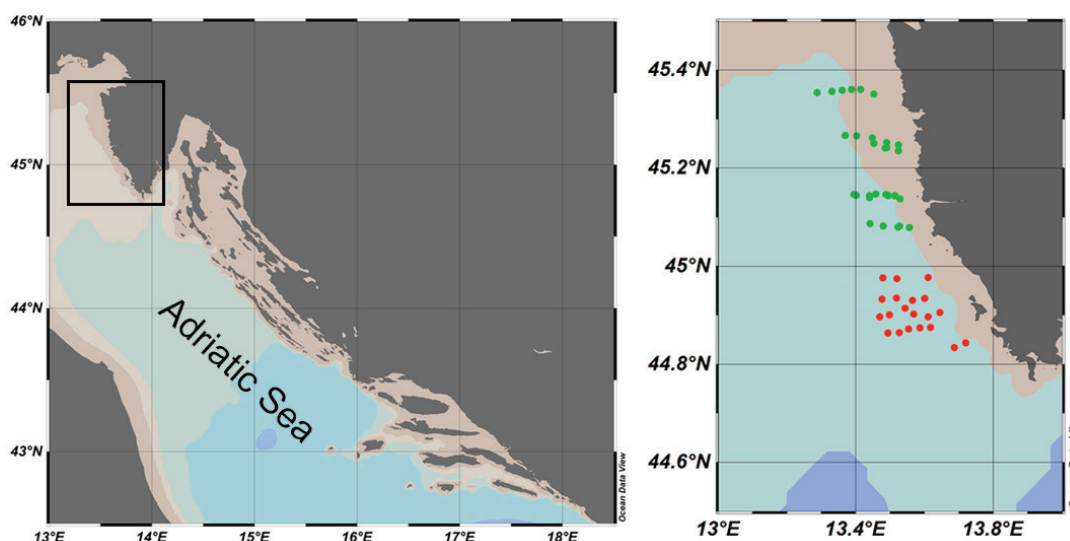
**Table 1.** Information about the performed tows.

	Beam trawl fishing area	Beam trawl non-fishing area
Speed (NM h <sup>-1</sup> )	5.0 ± 0.4	5.2 ± 0.4
Duration (min)	14.4 ± 4.6	7.8 ± 1.7
Tow length (km)	2.2 ± 0.7	1.3 ± 0.3
Depth (m)	29.6 ± 2.8	38.7 ± 1.4

limitations of the fishing vessel and characteristics of the survey area. Usual commercial tows in this area range between 20 and 30 min depending on the vessel characteristics and bottom community composition (e.g. amount of macrozoobenthic organisms). In total, 50 tows were performed, 29 in the beam trawl fishing area and 21 in the beam trawl non-fishing area. For each haul, the following data were recorded: latitude, longitude, minimum and maximum depth, duration of the haul and vessel speed.

### Sample collection and analysis

The catch was classified in three categories: i) target species that includes the commercially important bivalve species *Pecten jacobaeus* and *Ostrea edulis*; ii) commercial by-catch composed of non-target but commercially valuable species, mainly *Sepia officinalis*, *Eledone moschata* and *Solea solea*; iii) discard that includes non-commercial megabenthic invertebrates and commercial species below the minimum conservation reference sizes (MCRS). After each tow, catch was discharged on the vessel deck and all commercially important species were separated. The length and biomass of all commercial species were recorded. Biomass and abundance data were standardised to 1 km<sup>2</sup> and expressed as kg/km<sup>2</sup> and N/km<sup>2</sup> respectively.



**Fig. 2:** Survey area in the northern Adriatic Sea – green circles represent sampling sites in the beam trawl fishing area and red circles sampling sites in the beam trawl non-fishing area.

After selection of commercial species, the discard biomass was estimated by counting the number of standardised boxes and multiplying it by the average weight of ten full boxes. Additionally, discard sub-samples (4–8 kg) were collected from the nine tows in the beam trawl fishing area and seven tows in the beam trawl non-fishing area. The rest of the discard was returned to the sea immediately after analysis. Collected sub-samples were frozen until laboratory analysis. All organisms present in the discard were determined to the lowest possible taxonomic level, counted and weighted.

### ***Vessel monitoring system (VMS) and logbook data analysis***

VMS data together with fishermen's logbook data were obtained from the Directorate of Fisheries of the Croatian Ministry of Agriculture for the period from January to December of 2019. Although according to Council Regulation No 1224/2009 (EU, 2009) only vessels larger than 12 m need to have VMS, Croatia has more restrictive legislation and all beam trawl fishery vessels, regardless of length, are obligated to have VMS (Official Gazette 48/2015). VMS data contain series of geographical position (latitude, longitude), dates and times recorded by a global positioning system device (GPS). Those data are periodically sent by satellite to the monitoring station. For the Croatian part of the Adriatic Sea data, they are transmitted every 15 min. Furthermore, according to Official Gazette (144/2010), every fisherman needs to keep a logbook that includes the following information: i) vessel identification, ii) gear type, iii) dates of operation, iv) fishing location, v) information about the catch.

Data on the fishing activities from the logbooks were linked with the VMS data. The unique vessel identification number CFR (Community Fleet Register) was used to link vessels in the VMS and logbook databases. Logbook data were used to obtain data regarding the fishing gear and the catch. As VMS data usually provide continuous recording of the vessel position, collected data were filtered prior to analysis. VMS data were extracted for the period from a vessel's departure to its return to port. From the obtained data, those attributed to the fishing effort, selected based on the vessel's speed (4–6 NM/h), were used for the analysis. Duration of the fishing activities was calculated based on the difference between the last and first recorded ping for each beam trawl fishing vessel. If there were more signals between the two recorded efforts, which were determined as movements without fishing activity, that period was excluded from the analysis. Based on the VMS data (ping records), the spatial trajectories of each vessel were constructed. Maps with the density of the fishing effort and catch distribution of the target species were constructed in ArcGIS (10.7.1.) applying the Kernel Density function (resolution 250 m; stretch radius 1000 m). Fishing effort density was expressed in h/km<sup>2</sup> and the density of the overall landing and the landing of commercially important species was expressed as kg/km<sup>2</sup>.

### ***Statistical analysis***

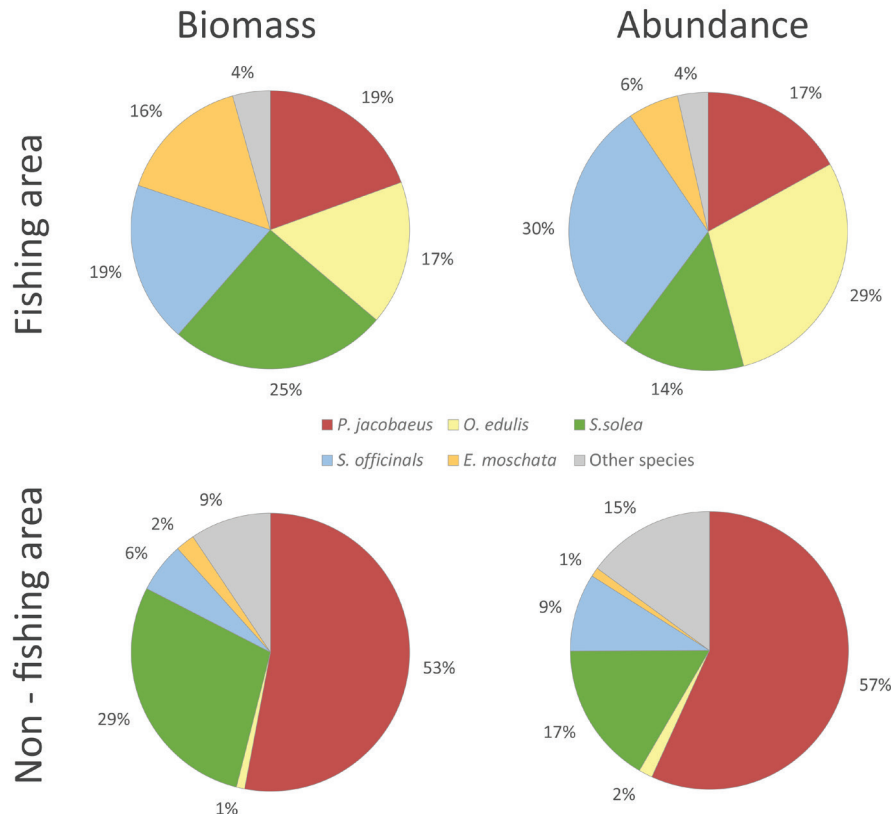
Standardised biomass data of the commercial catch were transformed using square root transformation. A non-metric multidimensional scaling (nMDS) plot was constructed based on the Bray–Curtis similarity matrix. To test whether the commercial catch composition differed between areas with different regulation, a one-way PERMANOVA with depth as covariable was applied (PRIMER-E Ltd, Anderson, 2001). SIMPER was performed to detect what species contributed most to the observed difference. The Kolmogorov–Smirnov test was used to test differences in species size distribution between the two areas. Furthermore, one-way PARMANOVA with depth as covariable and SIMPER were also applied for the discard groups based on their biomass contribution (%). The critical probability value was set at 0.05.

## **Results**

### ***Commercial catch composition***

In both areas, five commercial species were commonly present in the catch, the two bivalve species *Pecten jacobaeus* and *Ostrea edulis*, two cephalopod species *Sepia officinalis* and *Eledone moschata*, and one fish species *Solea solea*. In the beam trawl fishing area, in terms of biomass, all five species contributed almost equally, with a slightly higher proportion of *S. solea* (Fig. 3). The most abundant species in the commercial catch was *S. officinalis* (30%), followed by *O. edulis* (29%), *P. jacobaeus* (17%), *S. solea* (14%) and *E. moschata* (6%). In contrast, in the beam trawl non-fishing area, *P. jacobaeus* was the dominant species in terms of biomass and abundance and represented 53% and 57% of the total commercial catch, respectively. Among other species in the beam trawl non-fishing area, *S. solea* had the highest contribution followed by *S. officinalis* while the contributions of *O. edulis* and *E. moschata* were less than 2%. Biomass and abundance indices of those species are presented in Table 2. The largest difference between the two areas was recorded for *P. jacobaeus*, *O. edulis* and *S. solea*. *Pecten jacobaeus* and *S. solea* had higher indices in the beam trawl non-fishing area. In contrast, both cephalopod species and also *O. edulis* had higher indices in the beam trawl fishing area.

Besides the above-mentioned species, in the beam trawl fishing area an additional 11 commercially important by-catch species were recorded, eight fish species (*Chelidonichthys lucerna*, *Eutrigla gurnardus*, *Pagellus erythrinus*, *Penaeus kerathurus*, *Platichthys flesus*, *Scophthalmus maximus*, *Scorpaena porcus* and *Scyliorhinus canicula*), two crab species (*Maja squinado* and *Squilla mantis*) and one cephalopod species (*Sepia elegans*). Those by-catch species contributed 4% to the commercial catch, both in terms of biomass and abundance (Fig. 3). In the beam trawl non-fishing area, an additional 14 by-catch fish species were recorded: *Blennius ocellaris*, *Chelidonichthys lastoviza*, *Chelidonichthys lu-*



**Fig. 3:** Biomass and abundance composition of the commercial catch in beam trawl fishing and non-fishing areas in the northern Adriatic Sea.

**Table 2.** Biomass (kg/km<sup>2</sup>) and abundance indices (N/km<sup>2</sup>) of commercially important species.

Biomass indices	Beam trawl fishing area		Beam trawl non-fishing area	
	average per haul*±SD	average per area	average per haul±SD	average per area
<i>P. jacobaeus</i> **	103.3±106.8	74.4	537.0±383.8	510.9
<i>O. edulis</i>	67.8±81.5	64	8.1±18.6	9.2
<i>S. solea</i>	102.7±76.4	96.6	270.7±173.3	276.2
<i>S. officinals</i>	73.8±32.6	71.5	60.9±71.3	56
<i>E. moschata</i>	69.0±85.6	59.1	22.5±57.9	21.4
Abundance indices	average per haul*±SD	average per area	average per haul±SD	average per area
<i>P. jacobaeus</i> **	802±746	604	4.686±3.382	4,470
<i>O. edulis</i>	858±1003	841	124±292	126
<i>S. solea</i>	420±302	441	1.302±907	1,301
<i>S. officinals</i>	849±359	875	769±846	713
<i>E. moschata</i>	202±250	169	92±262	84

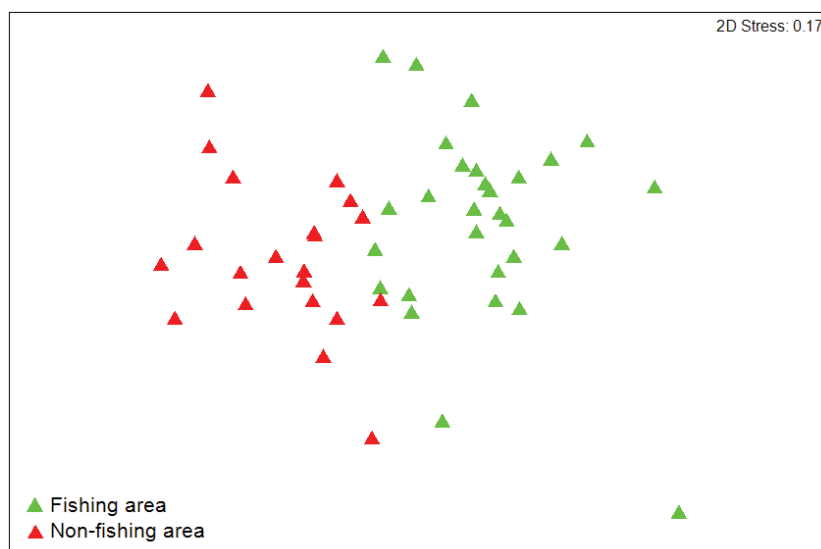
\* one haul represents catch of the two beam trawls during one tow

\*\* results for *P. jacobaeus* in commercial catch (specimens larger than 10 cm)

*cerna*, *Merluccius merluccius*, *Microchirus ocellatus*, *P. erythrinus*, *Raja asterias*, *Scorpaena notata*, *S. porcus*, *Scorpaena scrofa*, *Trachinus draco*, *Torpedo marmorata*, *Trisopterus capelanus* and *Zeus faber*. The contribution of those by-catch species to the commercial catch was 9% and 14% in terms of biomass and abundance, respectively.

Spatial segregation on the nMDS plot constructed based on the biomass indices of commercially important

species also revealed differences in the composition between the two investigated areas (Fig. 4). Furthermore, a one-way PERMANOVA test based on the biomass index data reveals that, when depth as a component of possible variation was included in the analysis, statistically significant differences existed between the two investigated areas (Pseudo-F = 10.793, p = 0.001; Table 3). According to SIMPER, *P. jacobaeus* contributed the most to the observed differences (28%), followed by *S. solea* (16%),



**Fig. 4:** nMDS plot based on the biomass indices of commercially important species in beam trawl fishing and non-fishing areas in the northern Adriatic Sea.

**Table 3.** Results of a one-way PERMANOVA test with depth as covariable for the catch and discard composition between two investigated areas.

Source	Commercial catch				Discard megazoobenthos			
	df	MS	Pseudo-F	P	df	MS	Pseudo-F	P
Depth	1	9966.6	13.363	<b>0.001</b>	1	2527.8	2.7044	0.059
Area	1	8049.9	10.793	<b>0.001</b>	3	4609.4	4.9316	<b>0.004</b>
Res	47	745.8			13	934.7		
Total	49				15			

*E. moschata* (12%), *O. edulis* (12%) and *S. officinalis* (9%). Average similarity among sampling sites in the beam trawl fishing area was 62% and among sampling sites in the beam trawl non-fishing area was 64%. Dissimilarity between beam trawl fishing and non-fishing areas was on average 51%.

#### Population structure of the commercially exploited stocks

The Kolmogorov–Smirnov test confirmed statistically significant differences ( $D = 0.285$ ,  $p < 0.001$ ) in the length distribution of *P. jacobaeus*, including both catch ( $\geq 10$  cm) and discard ( $< 10$  cm), between the two areas (Fig. 5). The average size of the *P. jacobaeus* from the beam trawl non-fishing area ( $9.8 \pm 1.2$  cm) was higher than the average size in the beam trawl fishing area ( $8.9 \pm 1.4$  cm) (Table 4). Furthermore, in the beam trawl fishing area, smaller individuals ( $< 10$  cm) dominated in terms of both biomass and abundance, while in the beam trawl non-fishing area both size categories contributed approximately equally (Fig. 5). It is also important to note that both size categories of *P. jacobaeus* were mostly without visible damage, while damaged specimens were only sporadically present in the catch. *Solea solea* length distribution between the two areas showed a non-significant difference ( $D = 0.0599$ ,  $p = 0.99$ ). Size frequency distributions in the two areas are presented in Figure 6. In the beam trawl fishing area, average

*S. solea* length was  $28.6 \pm 2.7$  cm, almost the same as in the beam trawl non-fishing area ( $28.6 \pm 6.6$  cm; Table 4). Significant quantities of *O. edulis* were present only in the catch in the beam trawl fishing area, while in the beam trawl non-fishing area this species was recorded only sporadically. Almost all specimens present in the beam trawl catch were larger than the minimal landing size, and the mean size in the beam trawl fishing area was  $7.9 \pm 1.0$  cm (Table 4). Among cephalopod species, both *S. officinalis* and *E. moschata* were represented, with larger individuals in the beam trawl non-fishing area in comparison with the beam trawl fishing area (Table 4). However, as a relatively low number was present in the catch in the beam trawl non-fishing area, differences in the length distribution were not statistically tested.

#### Discard composition

Regardless of the fishing area, discard contribution was high. In the beam trawl fishing area, discard made up on average  $97.8 \pm 1.8\%$  (range: 93.7–99.8%), while discard contribution in the beam trawl non-fishing area was even higher, on average  $99.1 \pm 0.5\%$  of the total catch (range: 97.9–99.8%). Analysed sub-samples in the beam trawl fishing area had on average 74% live megazoobenthos organisms while empty gastropod and bivalve shells and rocks made up the remaining 26% of sample mass. The contribution of empty shells and rocks in the sub-sam-

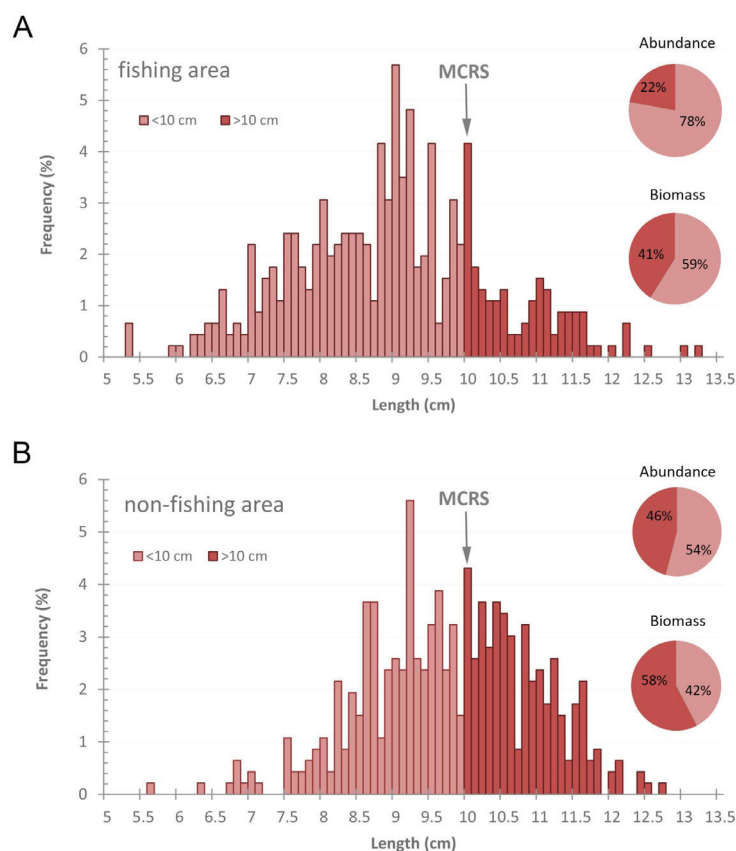
**Table 4.** Number of analysed specimens, size range and average size with standard deviation of the most common commercially important species in fishing and non-fishing areas in the northern Adriatic Sea.

	Beam trawl fishing area			Beam trawl non-fishing area		
	N	range	average±SD	N	range	average±SD
<i>P. jacobaeus</i> *	101	10.0-13.2	10.7±0.7	213	10.0-12.7	10.7±0.6
<i>O. edulis</i>	172	6.0-11.8	7.9±1.0	6	6.8-8.5	7.7±0.6
<i>S. solea</i>	85	23.0-36.0	28.6±2.7	62	23.5-34.5	28.6±6.6
<i>S. officinalis</i> **	181	5.5-11.0	7.8±1.1	34	6.5-10.5	8.2±1.3
<i>E. moschata</i> **	35	3.0-12.0	8.9±1.8	4	7.0-11.0	8.6±1.7
<i>P. jacobaeus</i> all***	457	5.3-13.2	8.9±1.4	464	5.6-12.7	9.8±1.2

\*Results for *P. jacobaeus* in commercial catch (specimens larger than 10 cm)

\*\*For cephalopod species, mantle length was measured

\*\*\*Results for all *P. jacobaeus* specimens caught



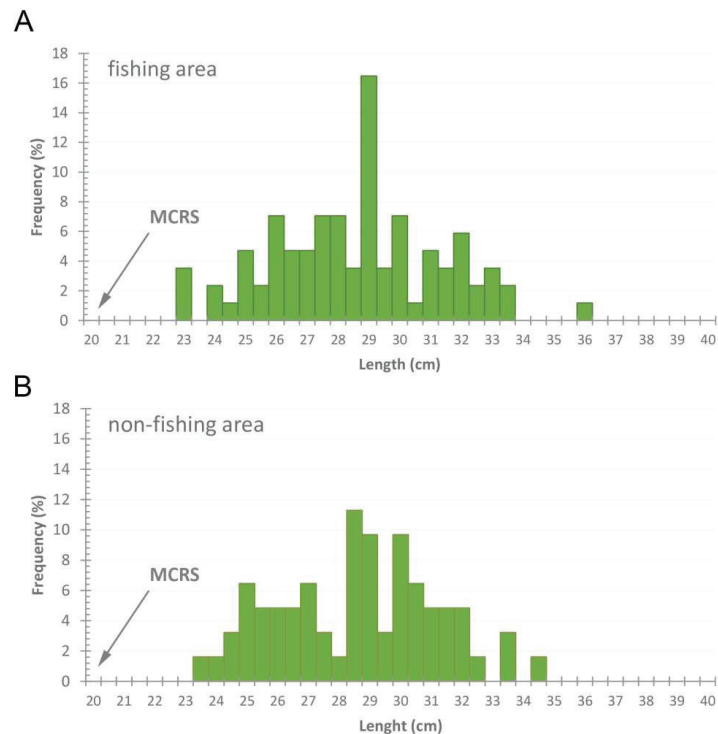
**Fig. 5:** Size distribution, biomass and abundance contribution of commercial size ( $\geq 10$  cm) and discard of *Pecten jacobaeus* in beam trawl (A) fishing and (B) non-fishing areas in the northern Adriatic Sea (MCRS: Minimum Conservation Reference Size).

ples in the beam trawl non-fishing area was higher and on average made up 40% of the analysed sub-samples. The biomass contribution of different taxonomic groups in the discard varied between the areas. In the beam trawl fishing area, Bivalvia had the highest contribution and made up 32%, followed by Tunicata (24%), Ophiuroidea (15%) and Porifera (15%), while other taxonomic groups contributed less than 8% each (Fig. 7). In contrast, in the beam trawl non-fishing area the dominant taxonomic groups in the discard were Porifera, making up 40% of the discard in terms of biomass (Fig. 7). Furthermore, Bivalvia contributed 17%, followed by Tunicata (16%)

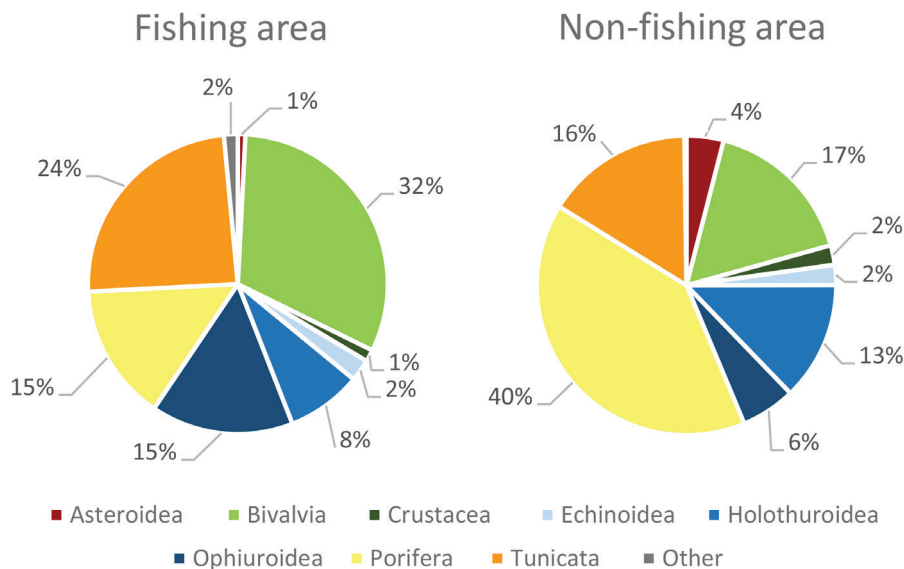
and Holothuroidea (13%), while the contribution of other taxonomic groups was less than 6% each (Fig. 7).

One-way PERMANOVA revealed significant differences in the composition of megabenthic invertebrates in the discard between areas (Pseudo-F = 4.9316,  $p = 0.004$ ; Table 3) and according to SIMPER average dissimilarity between areas was 52%. Groups that mostly contributed to the observed differences were Porifera (29%), Tunicata (21%), Bivalvia (20%), Ophiuroidea (11%) and Holothuroidea (8%) while the contribution of the other groups was less than 5% each.





**Fig. 6:** Size distribution of *Solea solea* in beam trawl (A) fishing and (B) non-fishing areas in the northern Adriatic Sea (MCRS: Minimum Conservation Reference Size).

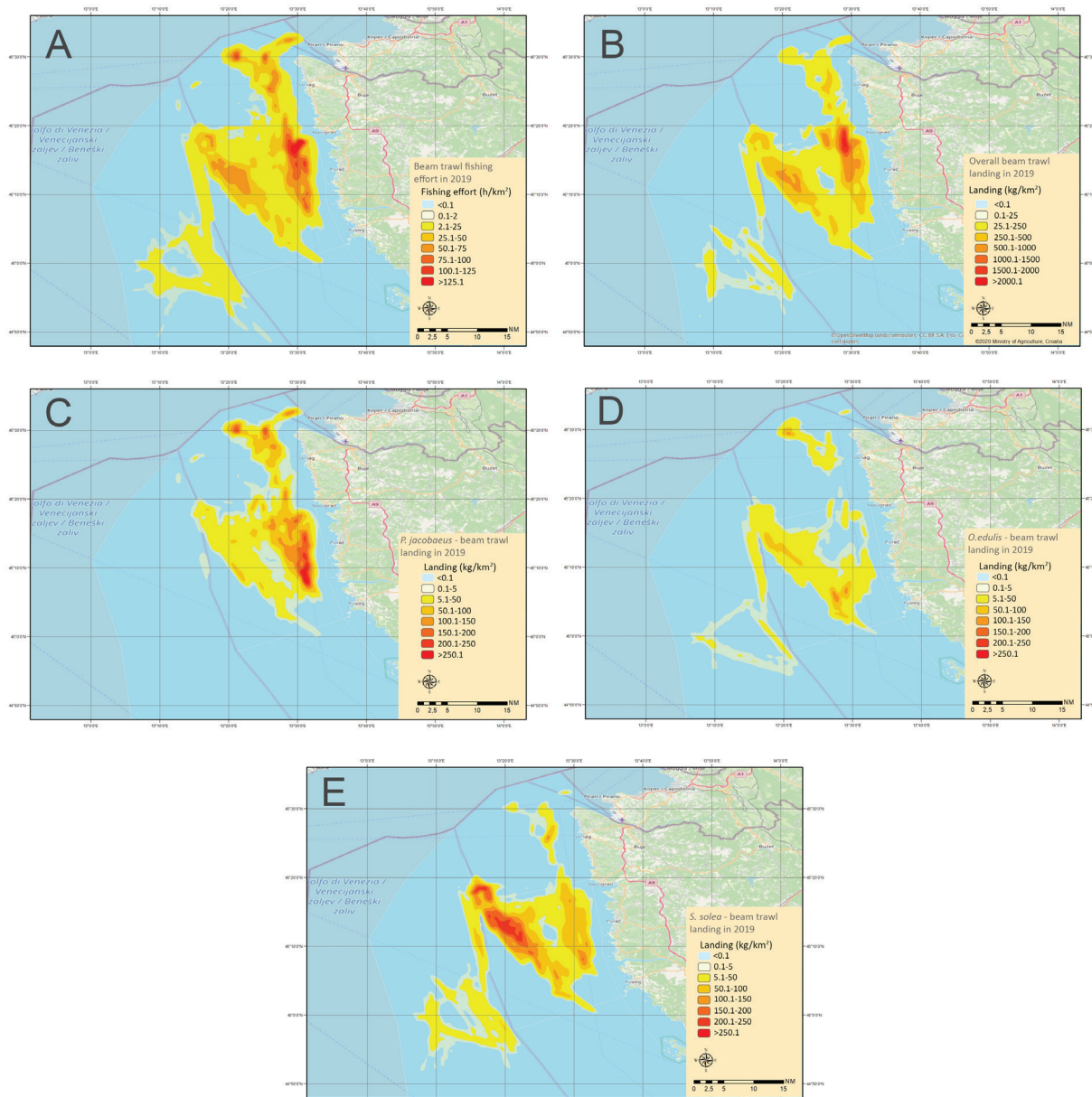


**Fig. 7:** Biomass composition of the megabenthic invertebrates in the discard in beam trawl fishing and non-fishing areas in the northern Adriatic Sea.

**Fishing effort and catch based on VMS and logbook data**

The analysed data for entire 2019 suggested that the greatest fishing effort coincided with the area with the highest overall catch (Fig. 8A and B). The maximal observed total landing was 2149.9 kg/km<sup>2</sup>. As this type of fishing gear is mostly focused on scallop species, it was

not surprising that the greatest fishing effort was recorded in areas with the highest biomass of *P. jacobaeus*, followed by areas where the biomass of *O. edulis* and *S. solea* was high (Fig. 8C–E). Maximal landing for *P. jacobaeus* was 313.0 kg/km<sup>2</sup>, followed by *S. solea* with 249.8 kg/km<sup>2</sup> and *O. edulis* with 135.8 kg/km<sup>2</sup>. Furthermore, the catch distribution suggests that areas where the two main exploited bivalve species, *O. edulis* and *P. jacobae-*



**Fig. 8:** Density distribution of beam trawl fishing effort (A), overall landing (B) and fishing grounds of *P. jacobaeus* (C), *O. edulis* (D) and *S. solea* (E) along the west Istrian coast in the 2019.

us, had the highest biomass are mostly spatially segregated. The area where *S. solea* showed the highest biomass corresponds to the area where the catch of the *O. edulis* was also the highest.

Seasonal analysis of fishing effort in 2019 showed that during the winter, spring and summer fishermen operated in the geographically wider area, while their activities during the fall were focused in the geographically narrower area (Fig. S2). Higher total landings were mostly observed in the area closer to the coast (Fig. S3). The landing of the *P. jacobaeus*, expressed as kg per km<sup>2</sup>, was higher during the spring-summer period (Fig. S4). The landing of *O. edulis* showed the highest seasonal oscillation with low landing during the summer and fall (Fig. S5). The landing of *S. solea* was higher in the fall-winter period (Fig. S6) with main fishing grounds in the more offshore areas.

## Discussion

### Population structure and spatial distribution of the commercially exploited species

The main beam trawl target species in the Croatian part of the northern Adriatic Sea is *Pecten jacobaeus*. Other types of fishing gear, such as bottom trawl nets, catch considerably less of this species in comparison with beam trawls and thus in the survey area this species is affected almost exclusively by the beam trawl fisheries. Furthermore, *P. jacobaeus* was the only commercially important species where a large amount of its catch corresponds to individuals smaller than MCRS, especially in the beam trawl fishing area. Although used gear has a relatively large mesh size (80 mm stretched mesh size) those smaller specimens probably remained in the net due to a

large amount of megazoobenthos discard. However, the majority of those specimens were without visible damage and during the regular fishing activities, they are returned to the sea immediately after each tow.

In the Croatian part of the northern Adriatic Sea, the *P. jacobaeus* population was investigated around 20 years ago (Cetinić & Soldo, 1999; Peharda *et al.*, 2003). Unfortunately, that research did not provide data about the biomass and abundance of *P. jacobaeus* and thus it is not possible to compare changes in its abundance. However, changes in the population structure are evident. In the survey by Cetinić & Soldo (1999), the largest recorded specimen was 15 cm long. A few years later, in the research conducted by Peharda *et al.* (2003), the largest specimen was 14.2 cm long and 13 years old. Based on length and age structure data, they assumed that under the fishing pressure then, overexploitation was not a problem. Nowadays, the data-poor stock model suggests that *P. jacobaeus* in the Adriatic exhibits a bad status with biomass below 50% of  $B_{MSY}$  and  $F$  much higher than  $F_{MSY}$  (Jaap Poos *et al.*, 2018). Considering that *P. jacobaeus* is relatively long-living species (Peharda *et al.*, 2003) observed difference in the population structure and abundance between areas with intensive beam trawl fishing and areas not affected by intensive activities is not surprising. Therefore we could assume that in the northern Adriatic Sea the level of exploitation of this species is an important issue that needs to be investigated in detail in the future.

The other target bivalve species of the beam trawl fisheries in this region is *O. edulis*. Although according to the official statistics this species contributed significantly to the beam trawl catch during the last decade (Fig. 1B), there is a lack of information about the natural beds that exist in the northern Adriatic Sea. According to Ezgeta-Balić *et al.* (2017), *O. edulis* was present at high density in the beam trawl fishing area during their research performed in 2013 and 2014; however, recently its abundance has decreased. This decrease is also confirmed by the landing data for *O. edulis* in the investigated area (Fig. 1B). Although exploitation might cause a decrease in the *O. edulis* population, other environmental factors that can cause natural mortality or a low recruitment rate (e.g. disease, global warming) cannot be excluded. A marked decrease in oyster bed abundance caused by intensive exploitation has also been reported in other regions (e.g. Smyth *et al.*, 2009). Low abundance of *O. edulis* in the beam trawl non-fishing area cannot be related to the fishing pressure as in that area there are no fisheries targeting this species. The abundance observed is most probably due to different distribution of the natural *O. edulis* beds.

Commercially, the most important by-catch species present in the beam trawl catch was the common sole, *S. solea*. In the Mediterranean and Black Sea regions, this species is considered to be overexploited (FAO, 2018, 2019). This species in the Adriatic Sea was investigated through SoleMon project (Grati *et al.*, 2013; Scarcella *et al.*, 2014), unfortunately, majority of the available data are for the western Adriatic, while only limited data is available for the eastern part of the Adriatic, including Croatian territorial water along the western Istria coast where

our study was performed. According to Jaap Poos *et al.* (2018), *S. solea* showed better status than *P. jacobaeus* in the Adriatic with biomass and fishing mortality slightly above  $B_{MSY}$  and  $F_{MSY}$ . The relatively better stock status of *S. solea* could be due to so-called “Sole Sanctuary”, a common sole spawning area that is located north from the Istria peninsula. In this area, it is difficult to operate with beam trawls and this probably ensures survival and successful reproduction of this species (Scarcella *et al.*, 2014). In our research, biomass indices differed between areas, with higher values in the beam trawl non-fishing area. However, those differences need to be interpreted with caution for two reasons, first as beam trawl landing of this species made up only a small portion of the total *S. solea* landing in this area and thus the differences observed are most probably not a consequence of beam trawl fisheries. Namely, unlike the target bivalve species, *S. solea* is mostly exploited with other types of fishing gear (trammel and gill nets) and their effect needs to be considered. Second, our study was performed over two consecutive years during the fall and considering the migration pattern of this species (Scarcella *et al.*, 2014) this could slightly affect obtained results. However, previous results from two scientific fishery-independent surveys, MEDITS and SoleMon, also confirmed higher abundance and biomass indices of the *S. solea* along the south-west part of Istria peninsula, which correspond to our beam trawl non-fishing zone in comparison with north-west part that corresponds to beam trawl fishing zone in this study (Grati *et al.*, 2013; Piccinetti *et al.*, 2012). An average abundance of the *S. solea* in the beam trawl fishing area was higher than those assessed during the SoleMon in 2005 and 2006 (between 25.1 to 250 individuals per km<sup>2</sup>; Grati *et al.*, 2013). In the beam trawl non-fishing area average abundance was in the range obtained during the SoleMon survey (between 250.1 to 2500 individuals per km<sup>2</sup>; Grati *et al.*, 2013). In general, considering available longer-term (2005–2016) data on the biomass and abundance indices from the SoleMon survey it is evident that both investigated areas had a several-fold higher indices in comparison with the average values for the Adriatic (Scarcella *et al.*, 2017). Although a difference in *S. solea* biomass was recorded between areas, the population size structure did not differ significantly. All *S. solea* individuals present in the beam trawl catch were larger than MCRS, mostly due to the migration ecology of this species. *Solea solea* adult individuals are present along the west coast of Istria while the main nursery area with juvenile specimens is located in the north-western Adriatic (Grati *et al.*, 2013). It is important to emphasize that the majority (>90%) of the specimens in both survey areas were also larger than 25 cm which is the estimated size at first sexual maturity (Jardas, 1996).

Cephalopod species in this study did not show any pronounced distribution pattern; however, they are short-lived species (<2 years) and their catch is highly dependent on recent recruitment (Challier *et al.*, 2005; Regueira *et al.*, 2015). Other commercially important by-catch species were present only sporadically in the catch during this survey and thus we assume that the direct effect of

beam trawl fishing on those species is mostly negligible. It also needs to be emphasized that in recent years commercial importance of other short-living small scallop species, such as *Aequipecten opercularis*, *Flexopecten glaber* and *Mimachlamys varia*, started to increase. Considering the status of the two main bivalve species exploited with beam trawl, *P. jacobaeus* and *O. edulis*, in the future we could expect higher exploitation of small scallop species.

### **Differences in benthic community composition between survey areas**

Although in the northern part of the Adriatic Sea different spatial persistence of megazoobenthos assemblages is confirmed (Santelli *et al.*, 2017) available data does not cover areas investigated in this study. Therefore, our study for the first time compares the structure of the megazoobenthos in the beam trawl fishing and non-fishing area in the eastern part of the northern Adriatic. It is well known that beam trawl fishing causes a disturbance and significant changes in the community structure of epibenthic species (Pranovi *et al.*, 2000). The contribution of the non-commercial discard in beam trawl fishing in the Adriatic Sea is high and makes up to 90% of the catch in the western Adriatic (Pranovi *et al.*, 2001). Our study confirmed an even higher contribution of the discard composed of non-commercial benthic organisms. Although a single experimental tow does not produce a significant effect on long-lived surface taxa (Pranovi *et al.*, 2000), commercial exploitation implies multiple trawling in the same area and therefore produces a cumulative disturbance on those species (Hinz *et al.*, 2009). Our study detected differences in the benthic community between beam trawl fishing and non-fishing areas. In the beam trawl fishing area, bivalves were the most common taxonomic groups in term of biomass. Among discarded bivalve species, the queen scallop *Aequipecten opercularis* was frequently recorded (Ezgeta-Balić, personal observation). This is in accordance with a video survey performed in the northern Adriatic, where the most abundant large epibenthic species was *A. opercularis* (Hall-Spencer *et al.*, 1999). In the eastern Adriatic, the commercial value of this species has started to increase recently; however, the majority of caught specimens are still returned to the sea as a non-commercial discard. In the beam trawl non-fishing area, the most common taxonomic groups in terms of biomass were sponges, one of the groups that due to their sessile life strategy are highly affected by trawl fisheries (Wassenberg *et al.*, 2002). Sponges were also the taxonomic group that contributed most to the differences observed in discard composition, with its lower contribution to discard in the beam trawl fishing area. Considering that scallop dredging causes a decrease in abundance and long-term changes in sponge assemblages (Kefalas *et al.*, 2003), this also justifies the lower contribution of this taxonomic group in the beam trawl fishing area. Similar differences in discard composition between the beam trawl fishing and non-fishing areas in the north-

ern Adriatic Sea were reported by Pranovi *et al.* (2000). In their research, molluscs (including gastropods and bivalves) were also dominant in terms of biomass in the commercially fished area while sponges were dominant in undisturbed areas.

### **Comparison of catch based on VMS and logbook data and on scientific survey data**

The obtained data confirmed that although the spatial distribution of the two target bivalve species overlapped, the areas where their catch was highest are spatially segregated to a certain degree (Fig. 8, Figs. S4-S6), which was also noticed during the survey (Fig. S1). Beside spatial differences, seasonal differences in the landing of three main species were observed. Considering that fishing ground with maximal landings of three most important species did not overlap entirely it can be assumed that fishermen choose fishing grounds depending on the market needs, that was reflected on the observed spatial and seasonal differences in fishing effort. Higher fishing effort in the area closed to the shore result in the higher landing of *P. jacobaeus* during the spring and summer, most probably due to the high market demand for this species during the touristic season. Furthermore, obtained data suggest that fishermen were targeting the *S. solea* fishing ground during the winter period that also corresponded to the area with the high landing of *O. edulis*. Actually, *O. edulis* was the species with most pronounced seasonal differences. During the winter and spring, this species landing was higher. During the summer, although according to the fishing effort data fishermen were operating in the *O. edulis* fishing grounds, oyster landing was rather low and spatially patchy distributed. This also supports previously observed decrease of the oyster abundance in this region.

Biomass indices calculated based on the scientific survey data were in accordance with the landing per area unit derived from the VMS and logbook data. This suggests that beam trawl fishery statistics collected through logbooks in the northern Adriatic provide reliable information and could be used as a good proxy for the changes in the main fishery resources in this region in the future.

In conclusion, this study presents the first comparative research on beam trawl catches in exploited and non-exploited areas that provides information about the potential effects of this type of fishing gear both on target and by-catch species in the eastern Adriatic Sea. Our results suggest that beam trawl fisheries mostly affect target bivalve species and non-commercial benthic species. The differences recorded between the study areas, together with previously available data, suggest that beam trawl fisheries cause changes in the *P. jacobaeus* population. Furthermore, a decrease of *O. edulis* abundance is confirmed. Considering the great efforts that are invested in the restoration of *O. edulis* habitats across Europe (e.g. Laing *et al.*, 2006; Smaal *et al.*, 2015), detection and protection of the natural oyster beds in the northern Adriatic are necessary. Overall, to revitalise this area, it is crucial

that future management plans both consider socio-economic issues and also take into account the long-term sustainability of the ecosystem.

## Acknowledgement

This work has been fully supported by the Directorate of Fisheries of the Croatian Ministry of Agriculture. Permission for fishing activity in the non-fishing area was obtained from the Ministry of Agriculture. The authors are thankful to Ivo Marušić, Vanja Vlahović and Vedran Vuletin for technical assistance in the field.

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## Supplementary data

The following supplementary information is available online for the article:

**Fig. S1:** Proportion of the three main commercially important species in the beam trawl catch during the survey in the northern Adriatic Sea. Larger circles represent larger biomass indices.

**Fig. S2:** Seasonal density distribution of beam trawl fishing effort during the winter (A), spring (B), summer (C) and fall (D) along the west Istrian coast in the 2019. (Q1 – first quarter includes period from January to March; Q2 - second quarter includes period from April to June; Q3 - third quarter includes period from July to September, Q4 - fourth quarter includes period from October to December).

**Fig. S3:** Seasonal density distribution of beam trawl fishing overall landing during the winter (A), spring (B), summer (C) and fall (D) along the west Istrian coast in the 2019. (Q1 – first quarter includes period from January to March; Q2 - second quarter includes period from April to June; Q3 - third quarter includes period from July to September, Q4 - fourth quarter includes period from October to December).

**Fig. S4:** Seasonal density distribution of beam trawl fishing landing of *P. jacobaeus* during the winter (A), spring (B), summer (C) and fall (D) along the west Istrian coast in the 2019. (Q1 – first quarter includes period from January to March; Q2 - second quarter includes period from April to June; Q3 - third quarter includes period from July to September, Q4 - fourth quarter includes period from October to December).

**Fig. S5:** Seasonal density distribution of beam trawl fishing landing of *O. edulis* during the winter (A), spring (B), summer (C) and fall (D) along the west Istrian coast in the 2019. (Q1 – first quarter includes period from January to March; Q2 - second quarter includes period from April to June; Q3 - third quarter includes period from July to September, Q4 - fourth quarter includes period from October to December).

**Fig. S6:** Seasonal density distribution of beam trawl fishing landing of *S. solea* during the winter (A), spring (B), summer (C) and fall (D) along the west Istrian coast in the 2019. (Q1 – first quarter includes period from January to March; Q2 - second quarter includes period from April to June; Q3 - third quarter includes period from July to September, Q4 - fourth quarter includes period from October to December).