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Effects of bottom trawling and hypoxia on benthic invertebrate communities.

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Running title (max 6 words): Benthic impacts from trawling and hypoxia

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Abstract

Marine benthic habitats in continental shelf regions are increasingly impacted by hypoxia caused by the combination of eutrophication and climate warming. Many regions that have the potential for hypoxic conditions are being fished by mobile bottom-contacting fishing gears. The combined effects of trawling and hypoxia may be synergistic and disproportionally impact benthic fauna, or they may act antagonistically, leading to smaller trawl impacts in hypoxic areas. Yet, few studies have quantified how bottom trawling and hypoxia interact to effect benthic communities. Here we examine these combined effects on benthic community biomass and abundance, the number of large organisms, the longevity distribution of the community and the vertical position of fauna in the sediment in the southern Baltic Sea. Our results show large declines in benthic biomass and abundance with declines in near-bed oxygen concentrations from 5.8 to 0.8 ml O₂ l⁻¹. Conversely, no effects and weak positive effects of bottom trawl disturbances are found on the benthic community. No interacting effects between hypoxia and trawling are detected. Our findings therefore highlight a low likelihood of synergistic impacts of bottom trawling and hypoxia on the benthic communities studied. These results suggest that management may prioritize benthic protection from fishing in regions that are not in a state of oxygen stress.

Keywords: bottom-trawling, hypoxia, Baltic Sea, macrofauna, body size, longevity, vertical position in sediment

1. INTRODUCTION

Marine benthic habitats in continental shelf regions are increasingly impacted by eutrophication-induced hypoxia (Diaz & Rosenberg 2008). Hypoxic regions are predicted to expand due to the warming of shelf waters with climate change, which increases both the oxygen demand and the strength of stratification of the water column (Breitburg et al. 2018). Many periodic hypoxic regions, such as the Baltic and Adriatic Seas, are currently also being fished by mobile bottom-contacting fishing gears, and these bottom trawl fisheries are the most widespread source of anthropogenic physical disturbance to seabed habitats (Amoroso et al. 2018).

Since management of nutrient loads and subsequent declines of hypoxic regions will take decades to centuries to occur, strategic management of bottom fisheries may be used to alleviate some of the impacts on benthic fauna and the ecosystem. Such strategic management requires quantifying the cumulative impacts of the two pressures on benthic fauna. The cumulative impacts of trawling and hypoxia may be synergistic when hypoxic conditions make organisms more sensitive to bottom fishing disturbance. Such effects may occur in areas where hypoxic and anoxic bottoms result in upward migration of burrowing organisms to the sediment surface (Pihl et al. 1992, Nilsson & Rosenberg 1994), thereby making these organisms more vulnerable to damage by bottom gears dragged along the seabed surface. Synergistic effects have also been proposed for brittle stars that became more sensitive to trawl disturbance due to arm-tipping behaviour, i.e. the elevation of the central disk to escape the low oxygen concentrations closest to the seafloor (Baden et al. 1990, Diaz & Rosenberg 1995). Under this scenario, management measures that protect hypoxic or hypoxia-prone areas from fishing may thus disproportionately benefit benthic fauna by reducing fishing-derived mortality of hypoxia sensitive fauna, and thus lowering the risk of benthic habitats being pushed into a permanently altered state (Riedel et al. 2016). Alternatively, when hypoxia leads to asphyxiation of sessile

fauna and/or migration of mobile fauna, leading to a depauperate state or even absence of benthic fauna, trawling may have a negligible additional impact on the benthos. Animals that can survive hypoxia events may also have physical characteristics that make them less vulnerable to trawling and trawling may not affect these species significantly. Fisheries management measures in such areas will have only limited benefits to the benthic ecosystem.

The above highlights that depending on the cumulative effects of bottom trawling and hypoxia, management of human impacts on benthic habitats may either prioritize protection from fisheries of hypoxic areas or prioritize the protection of areas that are non-hypoxic. So far, few studies have quantified the interactive effects of bottom trawling and hypoxia on benthic communities, limiting the development of management plans that consider the cumulative effects. Recent work on a continental slope off Vancouver Island found that bottom trawling continues to impact benthic communities in hypoxic areas, suggesting cumulative impacts that are either additive or synergistic (De Leo et al. 2017).

Here we study the effects of bottom trawling and hypoxia on benthic communities in the Baltic Sea. Throughout its historic past the Baltic Sea has seen hypoxic events on the seafloor (natural and human induced), mainly due to limited water exchange with the Atlantic and in recent decades excess nutrient input (Carstensen et al. 2014, Andersen et al. 2017). The Baltic Sea's benthic communities lack large habitat forming epifauna, in particular in the deeper areas. This is due to a low salinity, that in combination with its historic hypoxic past, has created the characteristically low species diverse, but highly abundant benthic communities (Bonsdorff 2006). Most of these benthic communities consist of short-lived fauna (Törnroos et al. 2015, 2019, van Denderen et al. 2019), which are predicted to be largely resilient to bottom trawling disturbance (Hiddink et al. 2018). Yet, approximately two thirds of the Baltic Sea bottom trawl fishing footprint occurs in areas with seasonal oxygen concentrations $<3.2 \text{ ml O}_2 \text{ l}^{-1}$ that may impact benthic organisms (van Denderen et al. 2019). It is therefore an area where trawling

93 impacts may be severely underestimated if synergistic effects are found to occur. The objective
94 of this study is to estimate interactive effects of bottom trawling and hypoxia on macrofaunal
95 biomass and abundance, large-bodied macrofauna, benthic community longevity and the
96 vertical position of fauna in the sediment. The studied stations ranged over a gradient in near-
97 bed oxygen concentrations from 0.8 to 5.8 ml O₂ l⁻¹ and in fishing intensity from little trawl
98 disturbance to up to 7 bottom trawl events per year. Our findings highlight a low likelihood of
99 synergistic effects between bottom trawling and hypoxia on the Baltic Sea benthic communities
100 studied.

2. MATERIAL AND METHODS

2.1 Study area

The effects of bottom trawling and hypoxia were examined over a gradient of oxygen and bottom trawling intensity in the Southern Baltic Sea in Polish waters (Fig. 1). The area is an active fishing ground with bottom trawling by otter trawls that target cod and flounder. The area was selected as earlier work showed it has gradients in oxygen concentration and bottom trawling intensity (van Denderen et al. 2019).

We selected sampling stations that covered a wide range of expected oxygen concentrations and trawling intensities on muddy sediment in a limited depth range (61 - 102 metres, Table S1-1), and aimed to cover all crossed combinations of trawling and oxygen to end up with a design where the effects of trawling and oxygen could be disentangled. Unsurprisingly, we could not identify any stations that had a high fishing effort at very low oxygen, as no fish can survive in those conditions, but we did sample several stations with fishing and relatively low oxygen concentrations (Fig. 2 and Table S1-1). All sampling stations were found in an area of 30 by 62 km, and the distance to the nearest station varied between 3 and 18 km.

2.2 Sampling of benthic fauna

Sampling was carried from on board the research vessel RV Oceanograf between 3 and 8 September 2018. Five replicate box corers and two replicate dredge samples were collected from each station. Box corer samples (catching area 0.06 m² per core) were taken in a star pattern, one at the selected position and four 100 m in each direction, using the vessel's Dynamic Positioning System. At times, the box corer came up empty or lost most of the sample before retrieval because the jaws did not close fully when pebbles or stones jammed the mechanism. When sampling was unsuccessful, the ship was moved 10s of meters and the box core redeployed. Three 4.5 cm diameter sub-cores up to a maximum depth of 17 cm were

collected from the first two intact box core samples collected at each station to assess the vertical distribution of fauna in the sediment in areas of different oxygen and fishing levels. Each sub-core was sliced into four sections (0-2 cm, 2-4 cm, 4-8 cm, >8 cm) and sieved to obtain the fauna at different sediment depths. The rest of the box core sample was sieved over 0.5 mm sieve. Most samples had a solid clay layer below a surficial mud, sand and/or gravel layer (surficial layer was ca. 8-18 cm deep); the clay layer was not sieved as no macrofauna can and did occur in this solid layer. To separate the smaller fauna from the remaining gravel and stones, samples were back-washed at least 7 times to obtain the fauna, by adding water, stirring the sample and draining the water over a sieve to capture suspended animals. The remaining sediment was checked for any further large fauna.

Semi-quantitative dredge samples were obtained using an Agassiz trawl type dredge (56 wide x 31 cm high, outer net mesh size 1 x 1 cm, inner net mesh size 0.5 x 0.5 cm), except for Station 1 (see below). The dredge was towed for 2 minutes at 1 knot and was generally full on retrieval. Samples were searched visually for fauna. Station 1 was sampled with a Naturalist dredge (60 cm wide x 30 cm high) that was towed for 10 and 5 minutes at 1 knot. We expect that the alternative methodology did not affect the resulting data in Station 1 as, in all cases, the dredge filled up quickly and stopped sampling afterwards. Inspection of the data does not suggest the dredge data in Station 1 is an obvious outlier.

All biota were identified to the lowest taxonomic level possible and their individual wet weight was measured. For dredge samples, where species abundance was greater than approximately 100 individuals, a subsample was taken per species. In the subsample, length was measured for all individuals whereas weight was measured for 50 individuals of a range of lengths. For the remaining individuals, we converted length to weight using the established length-weight relationship. We afterwards calculated abundance and biomass of the total sample based on the relative size of the subsample.

2.3 Environmental conditions

A sub-core measuring 4 cm in diameter core by 4 cm in depth was collected from the first box core sample collected at each station to determine sediment grain size composition. Particle size distributions were determined using a Malvern laser diffraction particle sizer (Blott & Pye 2001). Sediment particle analysis showed that most of the stations had a high percentage mud (Table S1-1). Visual inspection of the box cores showed that the muddy sediment was sometimes mixed with pebbles, gravel or sand and typically with a deeper layer of glacial clay. Some stations had ferromanganese nodules on the seafloor surface. A principal component analysis on depth and sediment conditions shows that stations 5 and 16 could be outliers due to a relatively high sand / gravel fraction, respectively (Fig. S1-1). Results showed similar patterns and trends when these stations were excluded from the analysis. It was therefore decided to maintain these stations within the analysis, despite small differences in sediment composition.

Bottom water was collected at 20 cm above the seabed with a Niskin bottle and oxygen saturation (YSI model 58) and temperature and salinity (WTW Multiset 340i with TetraCon 325) were measured from three replicate water samples collected at each station (with the exception of the first few stations where only a single measurement was taken) (Table S1-1). Temperature and salinity information was used to convert oxygen saturation into oxygen concentration in ml per litre following Benson and Krause (1984). A large fraction of stations was azoic, with concentrations below 1 ml O₂ l⁻¹ and with a strong smell of H₂S and a clear black surface layer. In addition to the oxygen measurements taken at the sampling stations, we analysed a time series of bottom oxygen concentration measurements collected from a nearby site at 90 m depth (red asterisk in Fig. 1) between 2012 and 2018. Monthly bottom oxygen concentration was calculated by averaging oxygen measurements at depths less than five

174 meters from the seafloor per month (where available). Data used were obtained from HELCOM
175 secretariat and based on ICES dataset on [Ocean Hydrography](#).

176 Bottom trawling intensity data were obtained at a $0.05^\circ \times 0.05^\circ$ grid resolution (ICES 2019),
177 and expressed as the ratio of the area that is swept each year by trawl gears relative to the total
178 surface area (hereafter termed swept-area-ratio, SAR). We used average SAR values per grid
179 cell for the period 2013-2017, as we were interested in chronic effects of fishing and since
180 recovery following trawling disturbance may last more than one year.

181 **2.4 Data analysis**

182 We analysed the effect of trawling and oxygen concentrations on community biomass and
183 abundance, the number of large organisms, the biomass-longevity distribution of the benthic
184 community and the vertical position of fauna in the sediment. In all analyses, we estimated
185 biomass and abundance as the sum of all box core or dredge samples per station. All results
186 show biomass of bivalves with shell. Since the biomass patterns are strongly driven by bivalve
187 weights, we verified that similar results are obtained when shell-free wet weight is used (based
188 on a wet weight to shell-free wet weight conversions as shown in Table S1-2). The dataset, R
189 scripts and output are available on Github with DOI: [10.5281/zenodo.5579600](https://doi.org/10.5281/zenodo.5579600).

190 Community biomass and abundance

191 We tested the effect of trawling and oxygen and their interaction on community biomass and
192 abundance with a Tobit regression model and selected the best model using the Akaike
193 Information Criterion (AIC); when models differ less than 2 AIC-units, the model with fewest
194 parameters is selected. Tobit regression is designed to estimate relationships assuming a normal
195 distribution for the response variable with left/right censoring, i.e. where a threshold value is
196 set to the response variable above/below the response variable data are censored (Tobin
197 1958). We used Tobit regression as it was expected that a range of sampling stations at low

oxygen concentrations had zero biomass and abundance and we therefore set the threshold for censoring our data at zero biomass and abundance. The community biomass and abundance analyses were done considering all stations, to examine the combined effect of trawling and oxygen concentration, as well as for a subset of stations with oxygen concentrations $> 3 \text{ ml O}_2 \text{ l}^{-1}$ to examine the effect of bottom trawling in isolation (Figure 2). The oxygen threshold value was chosen since benthic biomass and abundance no longer correlate with oxygen above this value.

Large organisms

Since previous work showed that the impact of bottom trawling is larger on larger benthic organisms ($> 4 \text{ mm}$) (McLavery et al. 2020), we included a separate analysis to study the effect of oxygen and trawling on the number of large organisms in the benthic community. The analysis used the same Tobit regression model as described above. We used two length thresholds: $>4 \text{ mm}$ and $>15 \text{ mm}$. We estimated individual length using length-weight relationships from the literature (Table S1-3).

Community longevity

Previous work has further shown that long-lived fauna are more impacted by bottom trawling (Rijnsdorp et al. 2018, Hiddink et al. 2018). We therefore examined the effect of trawling and oxygen on the longevity biomass distribution of the benthic community. We used the box core data to study changes in the biomass-longevity composition as these data provide a more controlled estimate of biomass (the dredge filled up quickly, as noted above). Using information on species longevity of benthic fauna in the Baltic Sea (Törnroos & Bonsdorff 2012, van Denderen et al. 2019), we classified biota in four longevity groupings: maximum lifespan of 0-1 years, 1-3 years, 3-10 years and > 10 years. The resulting taxon-by-trait matrix was combined with the taxon biomass-by-station (gram wet weight per 0.3 m^2) matrix to create the final station-by-trait matrix. We used a PerMANOVA analysis to examine if changes in

223 trawling intensity and/or oxygen concentrations had a significant effect on the distribution of
224 benthic biomass in these four longevity groupings. This analysis was done on absolute and
225 fractional biomass values per longevity grouping and sampled station.

226 Vertical position

227 We also used a PerMANOVA analysis to examine if changes in oxygen concentrations and
228 trawling intensity affected the vertical distribution of fauna in the sediment. Since the number
229 of observations was low in the vertical sub-cores, we limited our analysis to examining
230 community changes in the vertical position using the abundance and biomass data, whereas we
231 did not examine species-specific vertical changes. The analyses were done on absolute and
232 fractional abundance/biomass data per vertical section and sampled station.

3. RESULTS

3.1 Temporal and spatial stability in fishing and near-bed oxygen

We used average fishing intensities per grid cell for the period 2013-2017 to examine the chronic effects of fishing. A cross-comparison of fishing intensities between all years shows clear correlations, with an average Pearson product-moment correlation of 0.89. These strong correlations show there is temporal stability in the spatial fishing patterns studied. The studied gradient in fishing intensities is conserved in 2018, the year of sampling (Pearson correlation of 0.85 when compared with the annual average for the period 2013-2017), although the average level of fishing in the area in 2018 is marginally lower (average SAR in 2018 for all stations is 1.0, whereas it varies between 1.3 and 2.9 in the other years).

The time series of near-bed oxygen concentrations (Fig. 3a) shows large fluctuations between months, with maximum concentrations close to 5 and minimum less than 0.5 ml O₂ l⁻¹. The median near-bed oxygen concentrations are lower in summer and autumn (Q3 and Q4, Fig. 3b), although very low oxygen concentrations have been found in all seasonal quarters. The time series highlights that there are significant uncertainties in the temporal history of near-bed oxygen in our sampled stations (see further *Discussion* section).

3.2 Community biomass and abundance

The biomass of the community is dominated by the bivalves *Astarte elliptica*, *Mytilus trossulus* and *Limecola balthica* (formerly known as *Macoma balthica*). Together these species comprised 90% of total biomass in the box core data and 99% in the dredge. Abundance is dominated by the bristleworm *Scoloplos armiger* (27% of total abundance) in the box core data and by *A. elliptica* (81% of total abundance) in the dredge. No biota is found at stations with oxygen concentrations below 2 ml l⁻¹. All stations with oxygen concentrations above 3 ml l⁻¹ had some fauna.

We find a significant positive relationship between oxygen and both community biomass and abundance for both box core and dredge data (Fig. 4). In two of the four datasets (biomass and abundance from the dredge), trawling intensity has a significant positive effect (Table 1). An interaction term between oxygen and trawling intensity does not provide a better fit to any model (note that for box core abundance the interaction term has a p-value of 0.05, but the AIC value differs less than 2 units from a model without the interaction, Table 1). When analysing a subset of sampled stations with relatively high oxygen concentrations ($> 3 \text{ ml l}^{-1}$), trawling has no relationship with community biomass or abundance (Fig. 5).

To explore further the community response to trawling, we examined changes in biomass for the six most dominant species (in terms of biomass) in the box core samples and the five most dominant in the dredge samples collected at stations with relatively high oxygen concentrations ($> 3 \text{ ml l}^{-1}$). It is worth noting that all species have a non-significant relationship with oxygen in this subset (not shown). We find no significant relationship between biomass and trawling intensity for most dominant species, except for the priapulid worm *Halicryptus spinulosus* where a significant positive relationship is observed between its biomass and trawling in both dredge and box core data (Fig. 6).

3.3 Large organisms

Individuals larger than 4 mm comprised $>99\%$ of total biomass and 85% of total abundance. For these individuals ($n = 1587$), we find a significant positive relationship between oxygen and abundance and between trawling intensity and abundance (Table 1). Individuals larger than 15 mm comprised 30% of total biomass and 6% of total abundance. For these individuals ($n = 110$), there is again a significant positive relationship between oxygen and abundance, whereas tobit regression indicates no support for a model that includes trawling (Table 1). The dominant species contributing to the ‘larger than 15 mm’ group are the bivalve *A. elliptica* ($n = 34$), the isopod *Saduria entomon* ($n=19$) and the bristleworm *Terebellides stroemii* ($n=16$). The number

of individuals larger than 15 mm varies among stations between 0 and 21 per 0.3 m² (the sum of the five box cores); high numbers are only found in areas with relatively high oxygen concentrations (> 3.5 ml l⁻¹) (Fig. 7).

3.4 Community longevity

Almost 90% of the total biomass is grouped as fauna with longevity between 3 and 10 years and no species are found with lifespans more than 10 years. PerMANOVA analysis shows no support for a change in the biomass longevity composition of the community with changes in oxygen and/or trawling intensity (Table S1-4).

3.5 Vertical position

In total, 143 individuals are found in the vertical sub-cores across the stations. Most fauna (102 individuals, representing 90% of total biomass) are in the upper 0-2 cm of the sediment. Different polychaete species (*Pygospio elegans*, *Aricidea catherinae*, *Nereis diversicolor* and *Streblospio benedicti*), nematodes and ostracods are found in low abundance at depths deeper than 4 cm (in total 11 individuals, representing 1% of total biomass). PerMANOVA analysis shows no support for a change in the vertical distribution of fauna with changes in oxygen and/or trawling intensity (Table S1-5). The vertical biomass and abundance distribution is for each species shown in Figure S1-2 and S1-3.

4. DISCUSSION

We examined the effects of bottom trawl disturbance and oxygen on benthic community biomass and abundance, the number of large-bodied individuals, community longevity and the vertical position of fauna in the sediment. Our results show that changes in near-bed oxygen concentrations have a large impact on benthic fauna, whereas trawling had a weak positive effect on some species and community metrics and no effect on others. The lack of negative effects of trawling on most parameters, and a positive effect on some community metrics and the priapulid worm *Halicryptus spinulosus*, are somewhat unexpected given the high annual trawling frequencies at some sampling stations. We discuss below whether these non-negative effects may be a true effect or the result of different confounding factors. Whatever the reason, our findings highlight that bottom trawling appears to have limited impacts on the benthic communities studied here.

4.1 Non-negative trawl effects on benthic fauna

Bottom trawl impacts depend on the frequency of trawl disturbance, the amount of mortality (depletion) that bottom gears cause and the recoverability of the benthic community (Pitcher et al. 2017). The fisheries data shows that all trawling in the area occurs with a demersal otter trawl. This is a relatively light gear that is associated with a low depletion rate of 0.03, i.e. causing a biomass decline of 3% each time a benthic community is swept by this trawl (Hiddink et al. 2017, Rijnsdorp et al. 2020). All fauna in the studied region are further relatively short lived (<10 years), potentially the result of selection by environmental filtering due to low salinity and variable oxygen levels (Bonsdorff 2006). Short-lived species have relatively high recovery rates (Hiddink et al. 2018). Therefore, low trawl impacts may be expected in this area. Nonetheless, model predictions based on the observed longevity and the above depletion rate suggest a 20% decline of community biomass relative to carrying capacity in a location with a chronic fishing frequency of $SAR = 7$ a year (see SI 2 for the calculation). Although this is a

substantial effect, the variation in the recorded benthic communities is large due to natural variation and sampling error, and the power to detect such an effect may have been limited.

Biomass comparisons with the Kattegat and the more northern Gotland Basin reveal that box core biomass in our study area is on average 6 to 10 times lower than in those areas (Sköld et al. 2018, van Denderen et al. 2019). Since low oxygen conditions tend to affect relatively large areas homogenously, the low biomass in our study area may be the result of low and variable oxygen levels that have hindered recruitment and recolonization from neighbouring regions (Whitlatch et al. 1998). Recruitment in the Baltic Sea is also more stochastic and dependent on wind-induced waves since it is a non-tidal system (Valanko et al. 2010). It may therefore be hypothesized that any survivors and/or new arrivals in the area will have little competition for space and food and high growth rates, thus resulting in lower trawl impacts than expected.

The large fluctuations in oxygen concentration may also have limited our ability to detect negative bottom trawl effects given that we sampled at only one point in time. Some sampled stations with high oxygen measurements during our survey may have experienced lower levels in earlier months that would have killed a large fraction of the biota, causing a large amount of noise on the trawl impact signal. Nonetheless, all areas with relatively high oxygen concentrations were found to have some large-bodied (> 15 mm) individuals in the box core (Fig. 7). This suggests that the historic oxygen conditions were sufficient to allow the benthos to survive and grow to a large size. Moreover, most species sampled have minimal mobility so are unlikely to have moved from neighbouring regions.

We observed a positive relation between trawling and some community metrics and the biomass of the priapulid worm *H. spinulosus*. These increases may be linked to changes in the biomass and abundance of *Saduria entomon*, an important benthic predator in the Baltic Sea, with trawling. In field enclosure experiments, *S. entomon* has been found to have a negative

effect on priapulid abundances (Bonsdorff et al. 1995). *S. entomon* shows a negative trend with trawling intensity that albeit non-significant may have lowered predation pressure on infaunal prey in fished areas. Although speculative, the declining trend of *S. entomon* with trawling can itself also be driven by predation, since cod, an important predator on *S. entomon* (Neuenfeldt et al. 2020), may be found at higher abundances in areas of high fishing.

4.2 Low oxygen conditions and the absence of fauna

We found no benthic fauna in locations with oxygen concentrations less than 2 ml l⁻¹. Mass-mortality of benthic fauna typically occurs around 0.5 ml O₂ l⁻¹ (Diaz & Rosenberg 1995) and it is therefore likely that these sampling locations had lower oxygen levels earlier in the year. We also found no benthic fauna in Station 9, where an oxygen concentration of 1.3 ml l⁻¹ was measured. Station 9 is only 3.7 km away from the location with a time series of near-bed oxygen (Fig. 1, Fig. 3), making it likely that the time series reflect the temporal oxygen history of Station 9. The time series shows that oxygen concentrations dropped below 0.5 ml O₂ l⁻¹ in May 2018, which is four months before sampling. This drop is likely the moment where the mass-mortality occurred that led to the defaunation of Station 9. Importantly, in June 2018 oxygen concentrations were again 2 ml O₂ l⁻¹, showing the fine-scale temporal fluctuations in oxygen conditions. These results highlight that models predicting mortality on benthic fauna from hypoxia need near-bed oxygen data that captures these fine-scale temporal fluctuations in oxygen, as predictions will otherwise be at risk of significantly underestimating the effect. For example, all seasonal averages of the time series are well above 1 ml O₂ l⁻¹ and these values would not suggest a benthic defaunation of the area. A conclusion that warrants a reassessment of oxygen condition monitoring for assessing and disentangling seabed disturbance activities in the future.

The fishing intensity at Station 9 declined most severely in comparison to all stations, over the period 2013-2018. The station exhibited values close to SAR = 10 in 2013 and 1 in 2018. Fig.

S1-4 shows there is a strong and positive relation between the annual fishing intensities at Station 9 and the maximum yearly oxygen concentrations from the time series (linear model shows a p-value of 0.01 and an adjusted R^2 of 0.78), whereas no relation is found for minimum or average yearly oxygen conditions. This finding may imply that peaks in oxygen, which are still below 5 ml O_2 l^{-1} , attract fish and subsequently fisheries in this area. Catch rates of cod, an important target species, have been shown to peak at these intermediate oxygen conditions in the neighbouring Bornholm Basin (Neuenfeldt & Beyer 2003). Since cod feeds on pelagic sprat as well as benthic animals (especially motile ones), cod abundance may be high in areas where the state of the seafloor is low. This could explain why there is no relationship between trawling intensity and the average or minimum yearly oxygen conditions. If correct, there is an important temporal aspect to the interactive impacts of trawling and hypoxia on benthic fauna, where trawl disturbance will be highest in periods with relatively healthy oxygen conditions.

4.3 No synergistic effects

Despite significant uncertainties in the impact of trawling on benthic fauna and the temporal history of oxygen conditions, it is clear from our study that trawling impacts are not underestimated for this area because of clear synergistic effects between low oxygen conditions and trawling. Compared to other regions, two characteristics of the benthic community and the environment may have reduced the potential for synergistic effects in this area. Firstly, most samples had a deeper layer of glacial clay and few deep-bioturbating species; 99% of total biomass was found in the upper 4 cm. This limits the potential of increasing trawl impacts with hypoxia due to upward migration of burying organisms to the sediment surface as observed in other regions (Pihl et al. 1992, Nilsson & Rosenberg 1994), because all fauna is already found in the upper surface layers. Secondly, there were no ophiuroids and asteroids present in the area, limiting the potential of high trawl impacts with hypoxia due to arm-tipping behaviour.

This highlights that other regions with a different benthic fauna and sediment composition may show a different response, as is also observed by De Leo et al., (2017).

4.4 Management implications

Our results suggest that significant long-term improvements of benthic communities in this area are not to be expected when the area is solely protected from bottom trawl disturbance (even though significant negative effects of trawling in certain months of the year cannot be ruled out). Management of bottom trawl fisheries could therefore prioritize the protection of neighbouring non-hypoxic regions, under the assumption that trawl impacts do take place in these regions. Bottom fisheries management targeting non-hypoxic regions can thus be used to improve the overall status of benthic fauna in these specific areas within a relatively short period of time, which could have positive spill-over effects for neighbouring seasonal or more permanent hypoxic areas. Continued reductions of nutrient loads and subsequent declines of hypoxic regions would also benefit the state of the benthic ecosystem, but such management actions targeting eutrophication and hypoxia take decades before they yield positive results on the benthic ecosystem (Carstensen et al. 2014).

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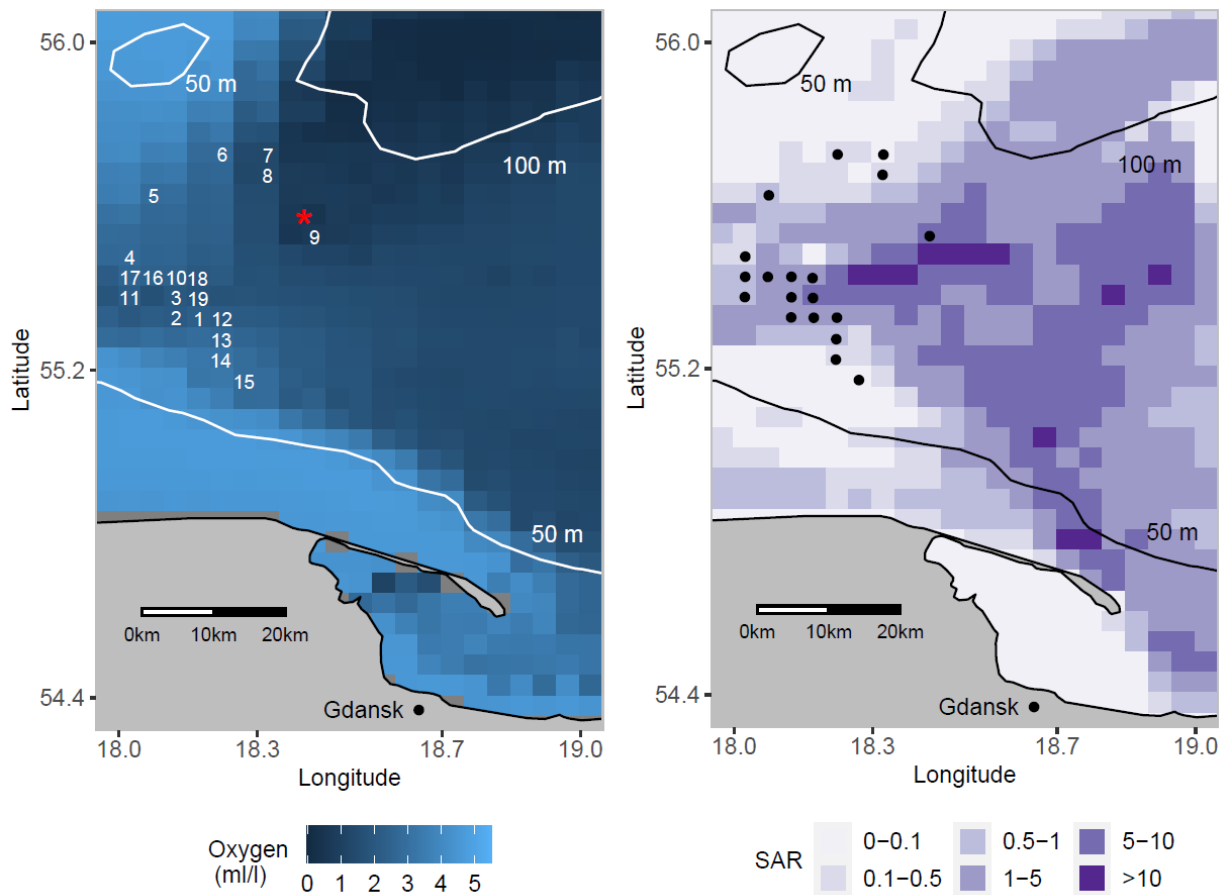
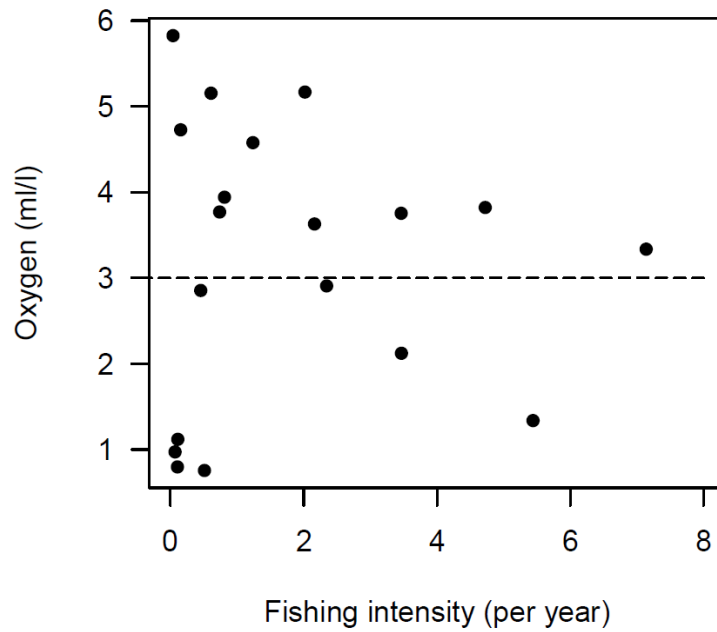


Figure 1. Maps of the sampling station locations in the southern Baltic Sea (numbers correspond to Table S1-1). The oxygen concentrations (left) show the lowest seasonal concentration in the year based on modelled bottom oxygen concentrations from an ecosystem model representative of 2006-2010 (Schernewski et al. 2015). The red asterisk shows a nearby location with time-series of near-bed oxygen measurements (see further Fig. 3). The fishing intensity data (right) show average SAR (Swept Area Ratio per year) values for the period 2013-2017. Depth contours were extracted from the Baltic Sea Hydrographic Commission (2013). The oxygen and depth data were solely used to select sampling stations as depth and oxygen data used in the analysis were measured in-situ at each station.



535

536 Figure 2. Fishing intensity (average SAR, per year) and oxygen concentration of the sampling
 537 stations. We analysed all sampling stations together to examine the combined effect of trawling
 538 and oxygen concentration, as well as a subset of stations with oxygen concentrations $> 3 \text{ ml O}_2$
 539 l^{-1} (stations above dashed line) to explore trawling effects in isolation. This threshold was
 540 chosen as no effect of oxygen on benthic biomass or abundance is observed above this
 541 concentration.

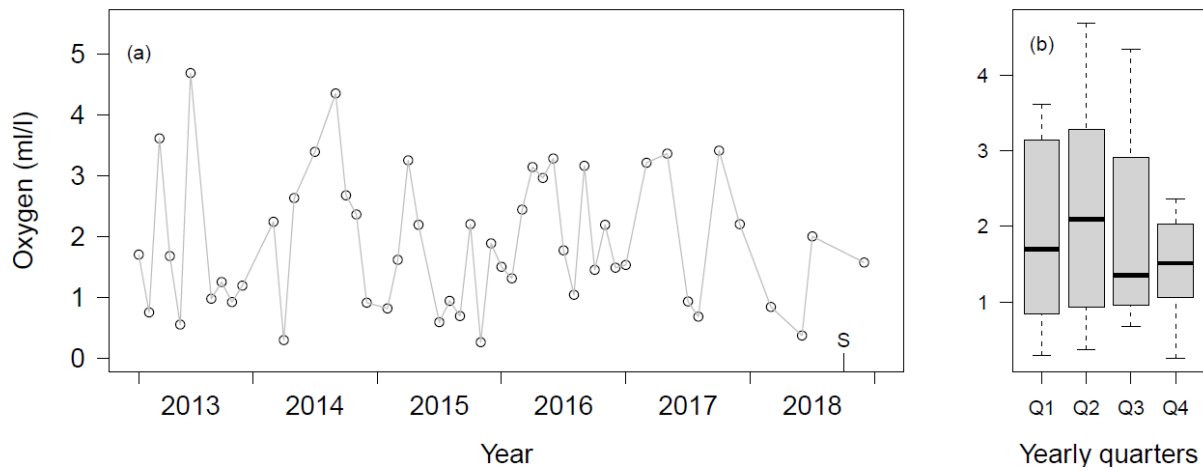


Figure 3. (a) Time series of near-bed oxygen concentrations at a nearby location of our study area (red asterisk in Fig. 1) from 2013 to 2018. The letter “S” indicates when we sampled the study area. (b) Boxplot of oxygen concentrations for each seasonal quarter based on all data points in (a), indicating lower median oxygen concentrations in quarter 3 and 4. Data used were obtained from HELCOM secretariat and based on ICES dataset on [Ocean Hydrography](#).

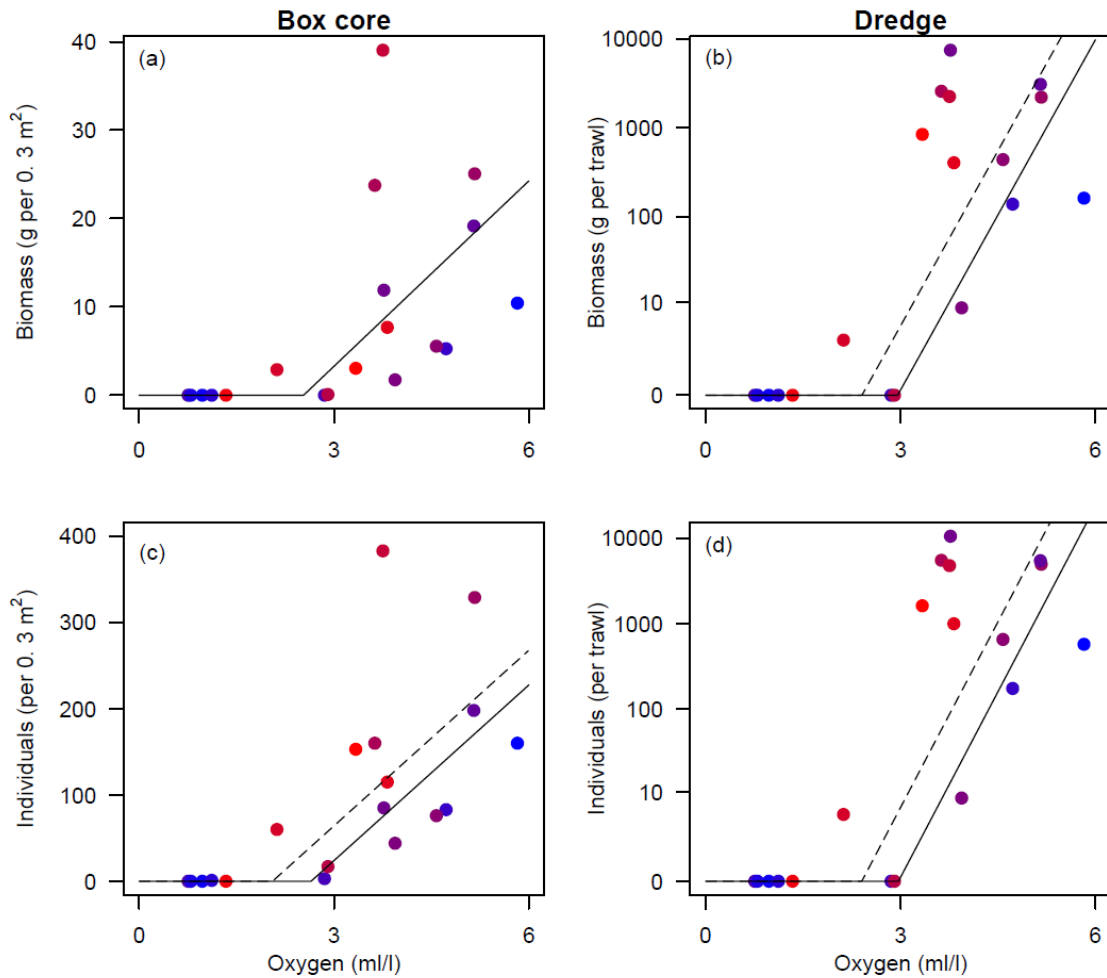


Figure 4. Relationships between oxygen and total faunal biomass and abundance collected using the box corer (a, c) and dredge (b, d). Lines are fitted with a Tobit-regression. In (b-d) where trawling intensity is part of the best model (Table 1), the solid lines show the prediction without fishing ($SAR = 0$) and the dashed lines with $SAR = 2$. Points are coloured using a linear colour gradient from the station with the lowest (blue, $SAR = 0.04$) to highest (red, $SAR = 7.14$) fishing intensity. The dredge data is $\log_{10}(x+1)$ transformed because there are four orders of magnitude variation between stations.

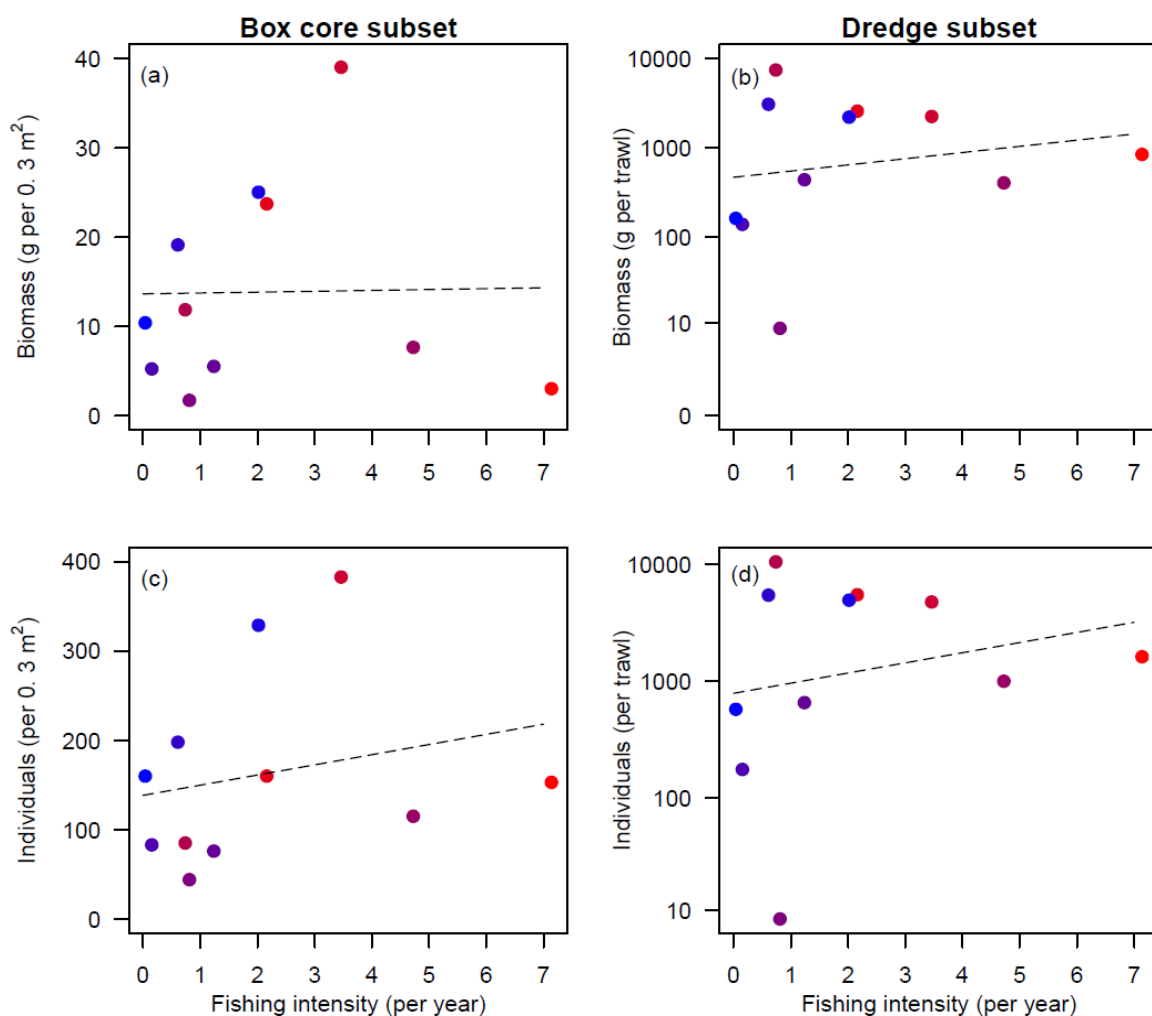


Figure 5. Relationship between fishing intensity (average SAR, per year) and faunal biomass and abundance of box corer and dredge for stations with oxygen concentrations above 3 ml l⁻¹. The relationships are all non-significant based on linear regression. Points are coloured using a linear colour gradient from the station with the lowest oxygen concentration (red, 3.3 ml l⁻¹) to the highest (blue, 5.8 ml l⁻¹) in this data subset.

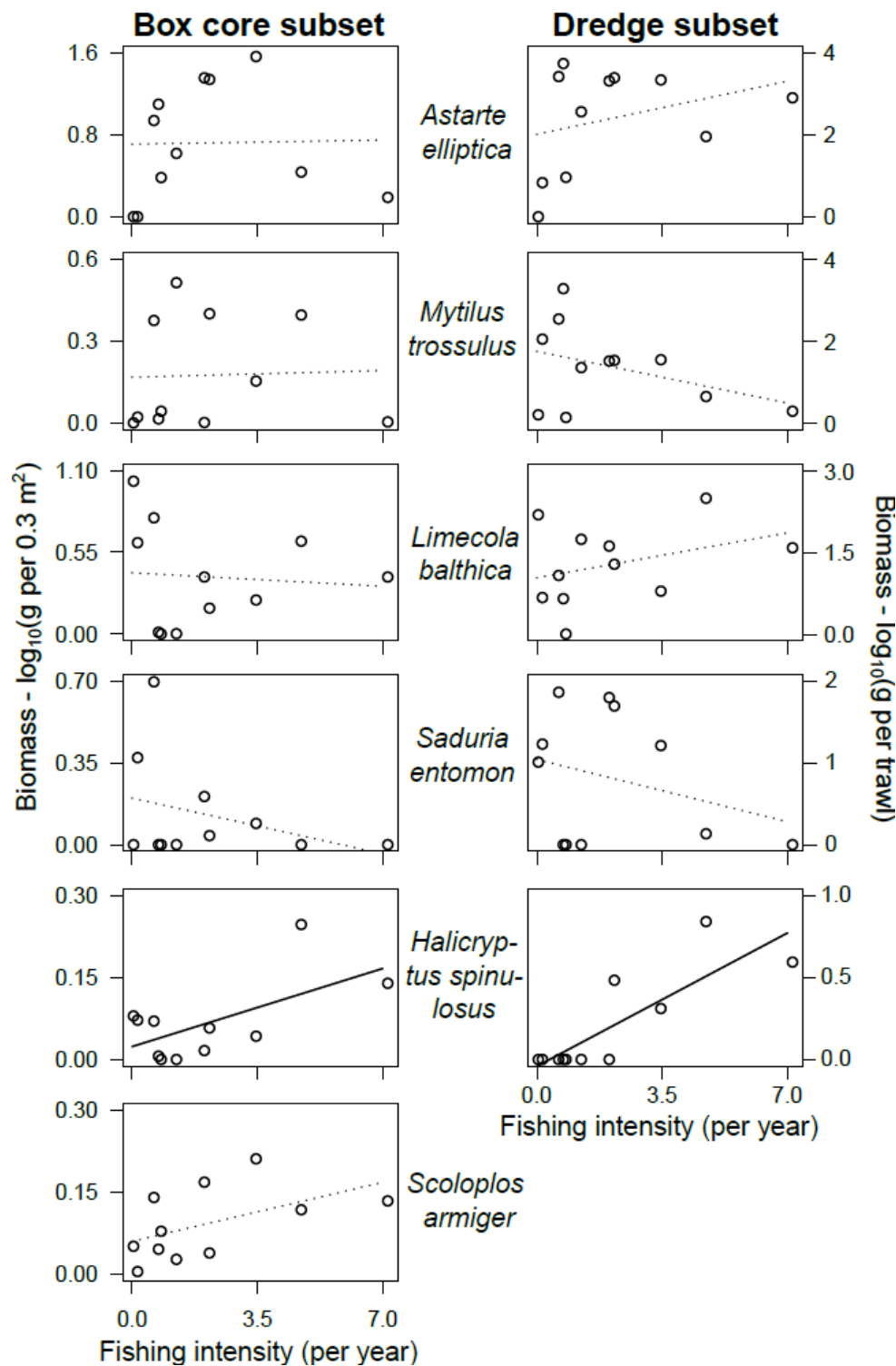
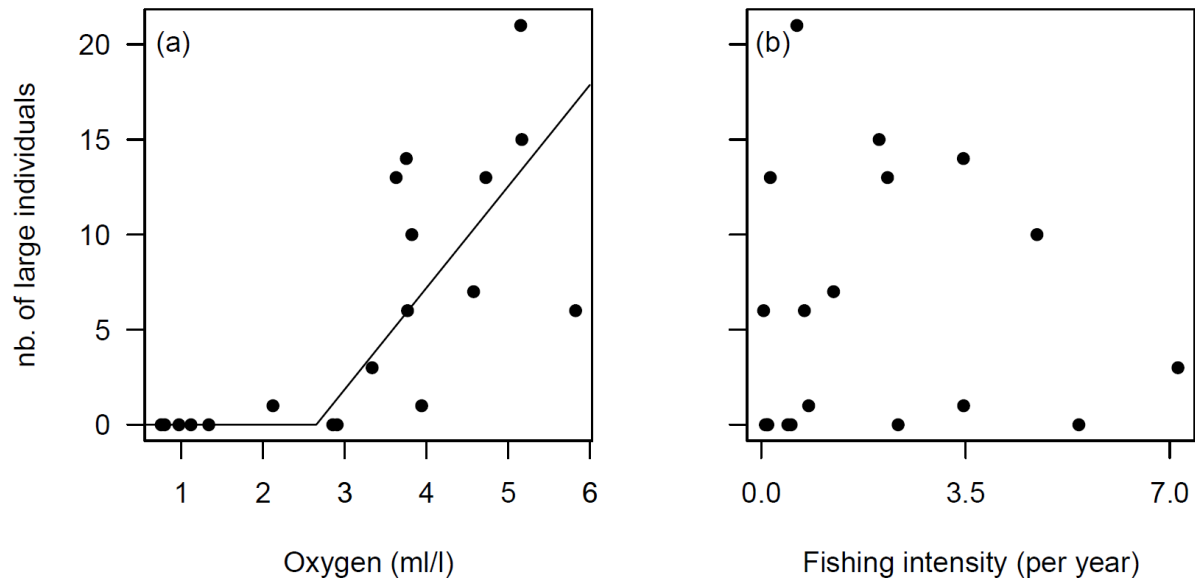


Figure 6. Relationship between fishing intensity (average SAR, per year) and the biomass of different dominant species in box corer and dredge for all stations with oxygen concentrations above 3 ml l⁻¹. Solid lines show significant relationships (p-value < 0.05), dashed lines non-significant. Note that all species in this subset have a non-significant relationship with oxygen concentration.



568 Oxygen (ml/l)

569 Figure 7. Relationships between the number of large individuals (>15 mm) and oxygen (a) and

570 fishing intensity (b) for all sampling stations. The solid line is based on Tobit regression. There

571 is no support for a model with trawling (Table 1).

Table 1. Model selection and coefficients. B is benthic biomass, A is benthic abundance, T is trawling intensity (year⁻¹) and O is measured oxygen concentration (ml l⁻¹). Tobit regression lower limit was set at zero biomass/abundance. The Tobit model includes an ancillary statistic, termed σ , which describes the log-standard deviation of the latent variable. Asterisks show best model based on AIC (when models differ less than 2 AIC-units, the model with fewest parameters is selected). Since Hauck-Donner effects were observed in some p-value estimates using Wald statistics, p-values were obtained by conducting a likelihood ratio test.

Model	σ	p-values	AIC
Box core biomass			
$B = -17.71 + 7.00 \cdot O$	2.35	$P_O < 0.001$	114.7*
$B = -23.37 + 7.58 \cdot O + 1.72 \cdot T$	2.32	$P_O < 0.001$; $P_T = 0.20$	115.1
$B = -16.11 + 5.54 \cdot O - 4.00 \cdot T + 1.73 \cdot T \cdot O$	2.27	$P_O = 0.01$; $P_T = 0.41$; $P_{T \cdot O} = 0.21$	115.5
Box core abundance			
$A = -132.65 + 65.44 \cdot O$	4.53	$P_O < 0.001$	187.7
$A = -179.66 + 67.86 \cdot O + 20.12 \cdot T$	4.43	$P_O < 0.001$; $P_T = 0.06$	186.3*±
$A = -110.58 + 46.60 \cdot O - 45.77 \cdot T + 20.71 \cdot T \cdot O$	4.32	$P_O = 0.005$; $P_T = 0.20$; $P_{T \cdot O} = 0.05$	184.4
Dredge biomass			
$\text{Log}_{10}(B+1) = -2.57 + 1.16 \cdot O$	0.24	$P_O < 0.001$	52.4
$\text{Log}_{10}(B+1) = -3.87 + 1.31 \cdot O + 0.36 \cdot T$	0.10	$P_O < 0.001$; $P_T = 0.03$	49.5*
$\text{Log}_{10}(B+1) = -2.70 + 1.01 \cdot O - 0.27 \cdot T + 0.19 \cdot T \cdot O$	0.03	$P_O < 0.001$; $P_T = 0.60$; $P_{T \cdot O} = 0.21$	49.9
Dredge abundance			
$\text{Log}_{10}(A+1) = -2.78 + 1.26 \cdot O$	0.30	$P_O < 0.001$	53.8
$\text{Log}_{10}(A+1) = -4.28 + 1.44 \cdot O + 0.41 \cdot T$	0.14	$P_O < 0.001$; $P_T = 0.02$	50.2*
$\text{Log}_{10}(A+1) = -3.02 + 1.12 \cdot O - 0.24 \cdot T + 0.19 \cdot T \cdot O$	0.07	$P_O < 0.001$; $P_T = 0.66$; $P_{T \cdot O} = 0.22$	50.7
Box core abundance (individuals >4 mm)			
$A = -161.08 + 66.60 \cdot O$	4.56	$P_O < 0.001$	176.6
$A = -252.91 + 76.43 \cdot O + 27.27 \cdot T$	4.42	$P_O < 0.001$; $P_T = 0.02$	173.3*
$A = -162.55 + 52.31 \cdot O - 29.86 \cdot T + 17.09 \cdot T \cdot O$	4.34	$P_O = 0.005$; $P_T = 0.45$; $P_{T \cdot O} = 0.12$	172.9
Box core abundance (individuals >15 mm)			
$A = -14.16 + 5.33 \cdot O$	1.71	$P_O < 0.001$	85.8*
$A = -18.72 + 5.98 \cdot O + 0.99 \cdot T$	1.69	$P_O < 0.001$; $P_T = 0.21$	86.3
$A = -14.34 + 4.86 \cdot O - 1.74 \cdot T + 0.78 \cdot T \cdot O$	1.65	$P_O < 0.001$; $P_T = 0.58$; $P_{T \cdot O} = 0.37$	87.5

± note that a model without trawling (model 1) differs less than 2 AIC values from the selected model (model 2). Yet, a model with interaction (model 3) is more than 3 AIC units lower than model 1. Model 2 is therefore selected as best intermediate model.