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| **Document title** | Influence of fishing pressure on benthic invertebrate species diversity and density in the Western Baltic Sea and evaluation of robust indicators for this taking into consideration hydrographical and physical habitat characteristics (initial results) |
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# Background

Within Theme 3 of the BalticBOOST project a series of test cases were set up early on with the general aim to groundtruth the linkages between pressures arising from human activities and the environmental status of seafloor habitats. Test cases were selected based on the availability of data from different areas and discussed and confirmed during the BalticBOOST Theme 3 WS 1-2016, held in Copenhagen, Denmark, 2-3 June 2016.

In the Femern Belt, the benthic monitoring program covered benthic fauna stations sampled under a carefully planned survey design with intensive, standardized, and repeated grab and frame sampling on seasonal basis in 2009 and 2010 on different types of benthic habitats and bottom depths. In particular, biodiversity (number of benthic species), density (number of benthic individuals) and biomass (weight of benthic fauna) were considered in the analysis. Fishing pressure was estimated as the fraction of the area (ratio of surface) covered by fishery (accumulated fishing effort) in a 1500 m radius from the benthic sampling stations and during a previous 3-month period of time. Hydrographical data, bottom depth, bottom current speed and sediment physical characteristics were also considered in the analysis. Three EUNIS level 3 habitats were relevant in this case: Sublittoral sand (A5.2), Sublittoral mud (A5.3) and Sublittoral mixed sediments (A5.4). Analysis was performed with simple correlation analyses followed up by complex multivariate statistical analyses of the fishing pressure impacts on the benthic community according to the many community and environmental parameters, which have been sampled with a very high resolution in time and space and with a very high number of observations. The estimates of fishing pressure in the analyses are ranging from low to high pressure.The preliminary results show that fishing pressure had a moderate but significant negative effect on biodiversity and density for all three habitats with a tendency towards higher impacts on the more course sediment. Fishing pressure seems not to have a strong impact on benthic community biomass. Accordingly, biodiversity and density seem to be rather strong indicators for impacts of fishery on the benthic invertebrate community with respect to different levels of fishing intensity, while benthic invertebrate community biomass seems not to be a strong indicator in this respect. It is evident that the positive correlation and impact of density on biodiversity needs to be taken into consideration when evaluating impacts on biodiversity. Also, it is evident that there are interaction effects and that fishing pressure has different impacts on the biodiversity and density in different habitats dependent on season of year. Overall, it seems that the impacts of fishing pressure on the benthic community diversity and density is in the same order of magnitude as the influence of natural hydrographical factors, e.g. current speed. The indicator density/biomass as well as the longevity indicator is in the process of being analyzed in the case study.

The meeting is invited to consider the information provided in this document.

# Influence of fishing pressure on benthic invertebrate species diversity and density in the Western Baltic Sea and evaluation of robust indicators for this taking into consideration hydrographical and physical habitat characteristics (initial results)

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## Introduction

The aim of the study is to evaluate ecological side effects of fishery with hauled gears in relation to impacts on the benthic environment, habitats and communities.

The following 0-hypotheses are tested:

- The species diversity (biodiversity=BD), given the number of individuals (density= N) of benthic invertebrates, is not affected by fishery and not dependent on different levels of fishing pressure (FP);
  - The above hypothesis is tested not only for BD but for several parameters (indicators):
    - BD given N,
    - N alone (density of invertebrates overall or by species for selected indicator species),
    - Biomass in dry weight (B in DW) given N (overall or by species for selected indicator species),
    - B/N (individual mean weight in the benthic community, i.e. on the overall community level, or by species for selected indicator species)
- There is no difference between different benthic habitats (seabed hardness types with different sediment grain sizes and types) and impacts of FP levels on BD (given N) - or on N or B alone or B given N or B/N - for benthic invertebrates;
- All species and species groups of benthic invertebrates are equally affected by different levels of FP;
- It is from the present data not possible to obtain robust indicators for impacts of different levels of FP among any species and species groups in the benthic invertebrate community.

## Materials and methods

### *Benthic Invertebrate Community Data*

Under the Environmental Impact Assessment (EIA) of a potential fixed link between Denmark and Germany benthic invertebrate fauna and physical habitat data were sampled and compiled by a consortium under the Femern Belt A/S (Danish Ministry of Transport) lead by the Danish Hydrological Institute (DHI) with participation of among other Institute of Oceanography in Warnemünde (IOW). Femern Belt A/S has granted full access to these data in present scientific context with data analyses and evaluations conducted by DTU Aqua. The benthic monitoring program covered benthic fauna stations sampled under a carefully planned survey design with intensive, standardized, and repeated grab and frame sampling on seasonal basis in 2009 and 2010 on different types of benthic habitats and bottom depths in the Femern Belt area of the Western Baltic Sea (Figure 1; Tables 1-2). Overall, 315 locations have been sampled throughout the second and third quarter of the year, and in total 1032 unique samplings have been taken under the monitoring program. The data sampling, the subsequent faunistic classification with phylogenetic and species determination, as well as the density and biomass estimation (wet and dry weight) by benthic group, have been quality checked and controlled by several independent experts to ensure high data quality.

Different types of invertebrate sampling gears were used, and each gear has different observation coverage area as shown in Table 1. The small Rahmen frame type which samples an area of 0.0625 $m^2$ was specifically used to sample blue mussels (*Mytilus edulis).* The data obtained with this sampling method are analyzed separately and not yet included in the current study. The stations included in the 6 samples with the dredge were also covered by Van Veen Grab sampling, and the dredge sampling did not provide any other information than the occurrence (presence/absence) of a species. Accordingly, the data from these 6 samples were also excluded. Finally, two samples that are on the sediment type 0 ("outside polygons") have been excluded from the analyses. An area conversion factor by sampling gear was used to standardize the analyzed number of individuals and the dry weight per species (Table 1), but not the biodiversity parameter (Table 1). The latter should be noted because there is observed a correlation between the number of species (BD) and the number of individuals (N). The differences between the covered areas of the different sampling gears are, however, so small (between 0.098 $m^2$ and 0.117 $m^2$) that there is no significant effect to be expected on BD by the different sampling areas. The majority of the data samples (69 %) have been area corrected.

Overall, 92 samples which provide quantitative FP and benthic invertebrate data where FP is above 0 (and excluding blue mussels) are used in the present analyses (Table 2).

Table 1. Overview of sampling gears used, their sampling area, the area standardization and correction factor by gear, as well as the number of samples conducted with each gear and method.

| **Sampling gear** | **Sampling area ($m^2$)** | **Area corrected** | **Number of samples** |
|---|---|---|---|
| Van Veen Grab | 0,0980 | 1,00 | 14 |
| Van Veen Grab | 0,1166 | 0,84 | 35 |
| Dredge | 0,1166 | 0,84 | 6 |
| Kautsky frame | 0,10 | 0,98 | 31 |
| Rahmen (0.1 $m^2$ mit Netzbeutel) | 0,10 | 0,98 | 9 |
| Van Veen Grab | 0,10 | 0,98 | 3 |
| Van Veen Greifer (0.1 $m^2$) | 0,10 | 0,98 | 2 |

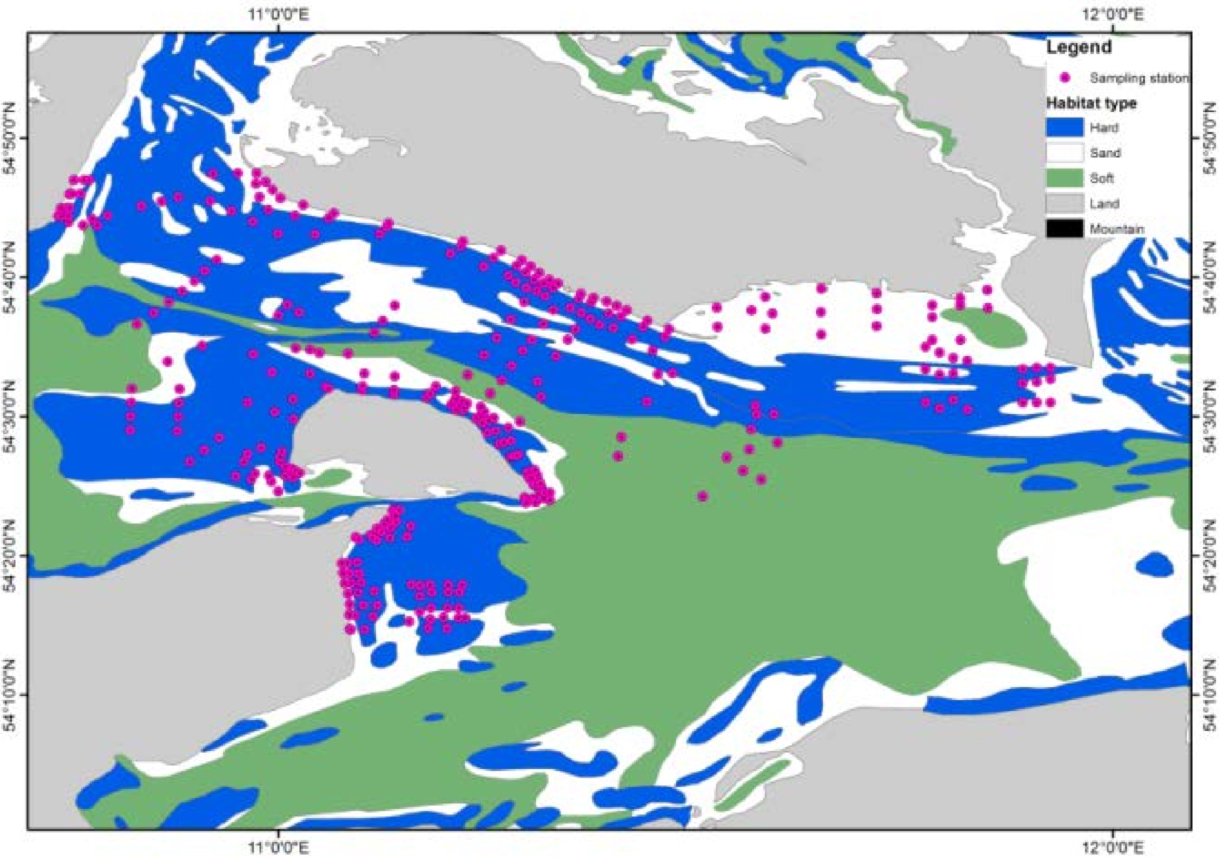


Figure 1. Grab and Frame sampling stations under the benthic invertebrate monitoring program and survey design (conducted by a consortium under Femern Belt A/S in 2009-2010) according to different types of benthic sediment types (physical habitats). Soft bottom is fine grained mud (sediment type 1), sand is sand (sediment type 2), and hard bottom is mixed sediments (sediment type 3).

*Fishing Intensity Data*

The fishing intensity or fishing pressure (FP) data comprise Danish and German VMS (satellite monitoring) fishing effort registration for vessels of 15 m length and longer using demersal hauled gears (mainly otterboard trawlers and otterboard pair trawlsers, but also seiners and dredgers). The fishing effort data have been extracted from national VMS databases and compiled and aggregated by DTU Aqua (Danish fishery data) and TI (German fishery data). FP estimates are obtained by processing the raw VMS data and making further coupling to fishery logbook data and to questionnaire surveys of fishermen and net makers with estimates regarding the dimensions of the different gears by applying the methodology described in Bastardie et al. (2010), Hintzen et al. (2012), and combined in Eigaard et al. (2016a,b). The relationships between gear dimensions and vessel size (e.g. trawl door spread and vessel engine power (kW)) for different gear groups were used to assign quantitative information of bottom contact (e.g. width of gear) to each logbook trip, and the extended logbook data were combined with interpolated vessel tracks based on VMS data (Hintzen et al., 2012). The required vessel size information, in terms of engine power (kW) and overall vessel length, was collected, together with the gear specifications in a pan-European industry-based questionnaire survey (Eigaard et al., 2016a). This study enabled statistical modelling of the vessel size or vessel engine power ~ gear size relationships for different métiers (combinations of gear types and target species) to deduce the width of the sweep of each of the (VMS interpolated) fishing event taking place across the stations.

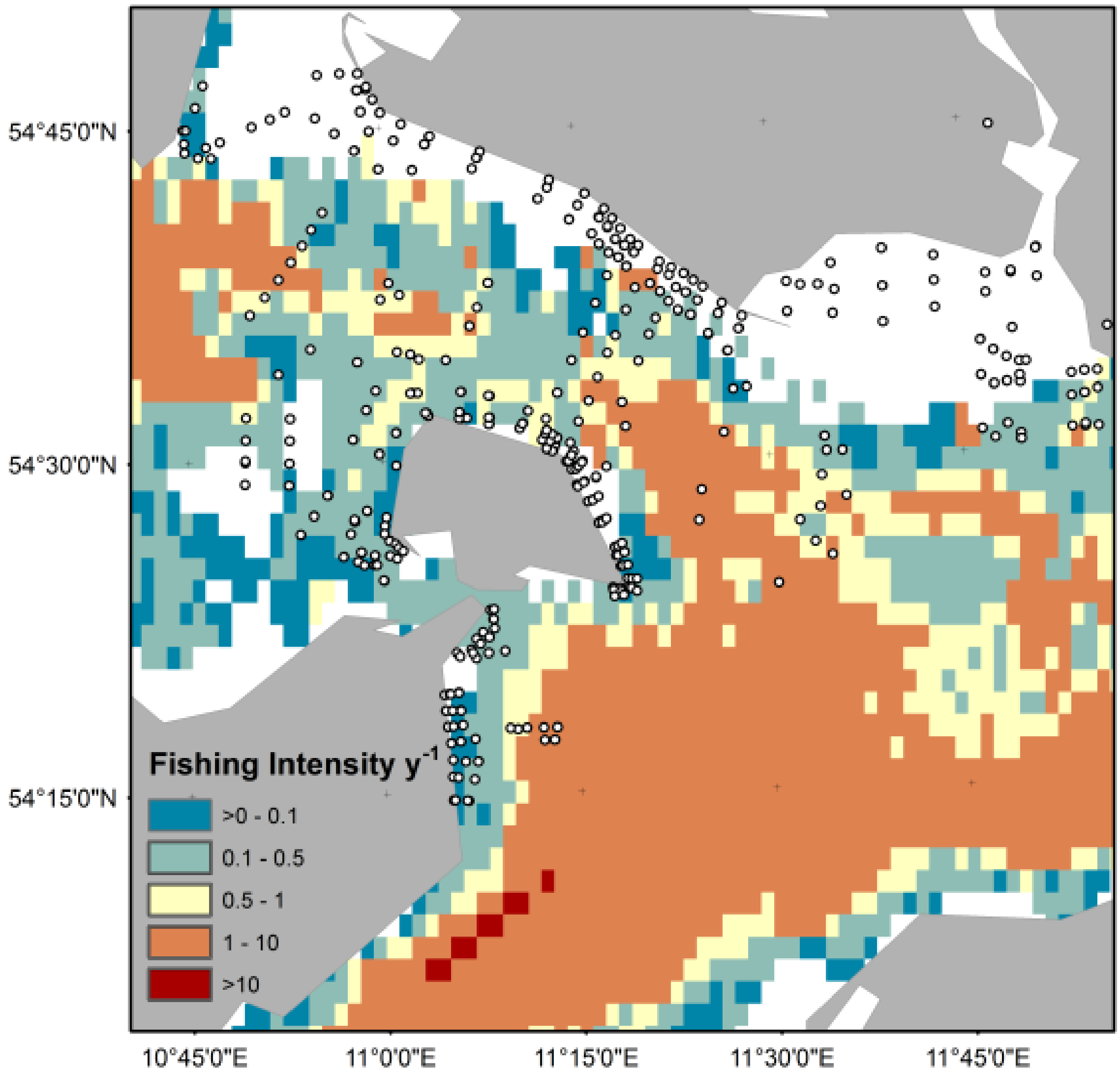


Figure 2. Fishing intensity (FP) by Danish, German (and Swedish) vessels (>= 15 m length) fishing with towed gears in the Femern Belt area in 2010. The Femern Belt invertebrate sampling stations are included in the map as well.

Fishing effort is accumulated within a radius of 1000 m (and alternatively 1500 m) around each of the benthic invertebrate sampling stations during the previous 3 months of the benthic invertebrate sampling date. That is 3 months before the current month of the sampling date (and alternatively only during the current month of the sampling date). The FP (fishing intensity) is estimated as the fraction of the area (ratio of surface) covered by fishery, i.e. accumulated fishing effort, in this 1000 m radius and 3 month period of time. That is, the total swept area inside a circle with radius 1000 m centered around each benthic sampling station coordinate so the FP is expressed as the swept area ratio (y-1) in form of the relationship between the area fished (swept) divided by the total station area. The circles surface areas were computed from UTM coordinates. Accordingly, if the FP parameter is 0.5 then only half of the 1000 m radius area is swept during the previous 3 month period which is the same as the full area is swept once after every second 3 month period. If the FP is 2 then the full area is swept by fishery 2 times within a 3 month period. The FP data resolution, processing and aggregation for estimating FP is following the EU-FP7-BENTHIS standards, and the EU FP7 BENTHIS WP2 software has been used for the process of estimating FP as described in Eigaard et al. (2016b) which is also based on previous work published in Bastardie et al. (2010) and Hintzen et al. (2012).

An example of the fishing pressure data for hauled gears in 2010 in the Femern Belt Area is shown in Figure 2. The relevant fishing effort and VMS data have been extracted and compiled according to unique identifiers based on position and time, and do take into account 0 FP as well. The FP data used for present analyses are from 2008-2010 with the calculated FP 3 months previous to the benthic invertebrate sampling (or in current month). Finally, the FP data have been merged with benthic invertebrate and physical habitat data by DTU Aqua using unique identifiers of date, position, and station number.

Table 2. Overview of the benthic invertebrate samples used in the present analyses including their spatio-temporal coverage. Furthermore, average fishing pressure by category is indicated as well as the minimum and maximum FP observed at stations in given category, i.e. the FP range included in the analyses.

| | Number of samples | Total Number of Species (BD) | Total Number of Individuals (N) | Total Biomass (B, g) | Average FP (Abrasion) | Minimum FP (Abrasion) | Maximum FP (Abrasion) |
|---|---|---|---|---|---|---|---|
| All Samples | 92 | 239 | 60068 | 2540,91 | 0,35 | 0,01 | 1,93 |
| 2009 | 50 | 215 | 29527 | 1090,93 | 0,27 | 0,01 | 1,56 |
| 2010 | 42 | 175 | 30541 | 1449,98 | 0,44 | 0,03 | 1,93 |
| Season 1 | 63 | 218 | 35819 | 1765,63 | 0,46 | 0,01 | 1,93 |
| Season 2 | 29 | 178 | 24249 | 775,28 | 0,10 | 0,04 | 0,55 |
| Habitat 1 | 35 | 135 | 23663 | 1790,65 | 0,44 | 0,05 | 1,93 |
| Habitat 2 | 3 | 55 | 977 | 21,36 | 0,39 | 0,03 | 0,87 |
| Habitat 3 | 54 | 228 | 35428 | 728,90 | 0,29 | 0,01 | 1,78 |

*Hydrographical Data and EUNIS Level 3 Benthic Habitat Data*

Hydrographical data, bottom depth, and sediment physical characteristics are obtained from two databases and a physical hydrodynamic model processing data available from the Danish Meteorological Institute (DMI). The used data have been extracted, processed and compiled by DTU Aqua. The physical data are produced by a Baltic-North Sea ocean-ice model HBM (HIROMB-BOOS Model) in the operational setup by DMI. A biogeochemical module (ERGOM) is dynamically embedded in the HBM. HBM is a three-dimensional, free-surface, baroclinic ocean circulation and sea ice model. The model allows for fully two-way nesting of grids with different vertical and horizontal resolution, as well as time resolution. The HBM setup for the present hydrographic dataset has a horizontal grid spacing of 6 nautical miles (nm) in the North Sea and in the Baltic Sea. In the vertical grid the model has up to 50 levels in the North Sea and the Baltic Sea with a top layer thickness of 2 m. At the surface, the model is forced with atmospheric data from the numerical weather prediction model HIRLAM (DMI) with 10 m wind fields, sea level pressure, 2 m temperature and humidity and cloud cover. Furthermore, freshwater runoff from the 79 major rivers in the region is obtained from a mixture of observations, climatology (North Sea rivers) and hydrological models (Baltic Sea). The extracted hydrographical parameters analyzed are near seabed temperature (t, °C), salinity (s, psu), oxygen concentration (o, mg $O_2$/l), and current speed (u, m/sec) as well as bottom depth (m). Monthly minima and maxima as well as the daily mean values for these parameters have been extracted for the benthic invertebrate sampling station positions.

Seafloor sediment data together with depths were extracted by DTU Aqua from the EUNIS level 3 databases processed and compiled for the benthic invertebrate sampling positions using EU-FP7-BENTHIS standards described in Eigaard et al. (2016b). Three EUNIS level 3 habitats at location of benthic invertebrate sampling were relevant here: 1 Sublittoral sand (A5.2), 2 Sublittoral mud (A5.3) and 3 Sublittoral mixed sediments (A5.4). Some stations did not have sediment data available and they were categorized as 'outside polygons' and this category only includes 2 samples where FP was above 0 (not used).

*Initial two-way correlation analyses*

Initial stage two-way correlations were investigated between BD (total number of species per sample), density N (total number of individuals counted per sample), biomass B (total biomass per sample), cumulative FP (3 months previous to the month of sampling date), bottom temperature, oxygen concentration, and salinity (all as minima within the sampling month), and current speed (maximum within the sampling month), as well as the season and the type of habitat / sediment classified in the above 3 categories 1-3. Furthermore, single species correlations were investigated for selected species between FP and both N, and B (but naturally not for BD in these cases). The method used for the two-correlation analyses was the Lowess-smoother performed in R (R Core Team 2015).

Table 3. Overview of selected tested statistical models with different types of dependent and explanatory variables included, as well as model settings. The overall R-square of the model and the deviance (the proportion of the variability) in the data explained by the model are given as well.

| **Model Number** | **GAM Model analysed within the R statistical software** | **Model $R^2$** | **Deviance Explained** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Model 1 | Biodiv ~ N_ind + FP_cum + t_min + s_min + o_min + u_max + sed_type + (1\|year) + te(lon,lat) | 0,88 | 84,4 % |
| **Model 2 (Baseline)** | **Biodiv ~ N_ind + FP_cum + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat)** | **0,88** | **84,9 %** |
| Model 3a | Biodiv ~ N_ind + FP_cum + u_max + sed_type + (1\|year) + te(lon,lat) | 0,87 | 83,6 % |
| Model 3b | Biodiv ~ N_ind + FP_cum + t_min+ sed_type + (1\|year) + te(lon,lat) | 0,86 | 82,0 % |
| Model 3c | Biodiv ~ N_ind + FP_cum + s_min + sed_type + (1\|year) + te(lon,lat) | 0,86 | 82,3 % |
| Model 3d | Biodiv ~ N_ind + FP_cum + o_min + sed_type + (1\|year) + te(lon,lat) | 0,87 | 83,6 % |
| Model 4 | Biodiv ~ N_ind + FP_cum + depth + sed_type+ (1\|year) + te(lon,lat) | 0.88 | 83,1 % |
| Model 5 | Biodiv ~ N_ind + s (FP_cum) + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat) | 0,92 | 89,9 % |
| Model 6 | Biodiv ~ N_ind + t_min + s_min + o_min + u_max + quarter * sed_type * FP_cum + (1\|year) + te(lon,lat) *(Incl. 1st order interactions between season, sed. type & FP)* | 0,89 | 86,0 % |
| Model 6c | Biodiv ~ N_ind + t_min + s_min + u_max + FP_cum:sed_type + FP_cum:quarter + (1\|year) + te(lon,lat) | 0,89 | 86,0 % |
| Model 7 | N_ind ~ FP_cum + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat) | 0,52 | 60,2 % |
| Model 8 | Biomass ~ FP_cum + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat) | 0,02 | 6,8 % |
| Model 9 | Biomass ~ N_ind + FP_cum + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat) *(Biomass considering density)* | 0,02 | 6,9 % |
| Model 10 | N_ind ~ t_min + s_min + o_min + u_max + quarter * sed_type * FP_cum + (1\|year) + te(lon,lat) | 0,53 | 61,1 % |
| Model 10b | N_ind ~ s_min + o_min + u_max + FP_cum:sed_type + FP_cum:quarter + (1\|year) + te(lon,lat) | 0,52 | 60,5 % |
| Model 11 | Biomass ~ FP_cum + t_min + s_min + o_min + u_max + quarter * sed_type * FP_cum + (1\|year) + te(lon,lat) | 0,02 | 7,0 % |
| Model 12 | Biomass/N_ind ~ FP_cum + t_min + s_min + o_min + u_max + quarter + sed_type + (1\|year) + te(lon,lat) | 0,44 | 58,6 % |
| Model 13 | Biomass/N_ind ~ s_min + o_min + u_max + quarter * sed_type * FP_cum + (1\|year) + te(lon,lat) | 0,46 | 59,5 % |

*Statistical analyses and model for multi-variate analysis of variance*

A general additive model (GAM) with mixed effects was used in the statistical analyses of the same parameters (Table 3) as investigated in the initial correlation analyses. The dependent variables on benthic community level were BD, N, B, and B/N, respectively, and the explanatory variables were FP, habitat type (spatial explicit), season, year, individual hydrographical parameters, and depth. For the BD and N integer (count) dependent variables a negative binomial distribution and logit as the link function was used with the possibility of estimating over-dispersion. The negative binominal distribution was used as this model does not assume dependency between the mean and the variance in the distribution. For the continuous B and B/N dependent variables a tweedy distribution was used. A mixed models design was used for all models with year as a random effect and with the other explanatory variables as fixed effects (Table 3). A spatial component with tensor (te) between longitude and latitude was added allowing inclusion of the spatial and station variability, i.e. the variability between observations. Alternative model versions were compared. Significant effects were identified for each model using backwards elimination of insignificant model terms, and their statistical significance was estimated. Furthermore, model estimates of the dependent variable according to the impact of the explanatory effects were provided. The overall variability in the data explained by the model (estimation of deviance) was also estimated. Over-dispersion according to the negative binomial distribution, residual plots, and Q-Q plots were inspected for deviations from homoscedasticity and homogeneous distribution. Variance inflation factors were inspected to check for collinearity. All analyses were performed in R (R Core Team 2015) using the package lme4 and lmerTest (Bates et al. 2015).

The most important models tested so far are listed in Table 3. Some of the models tested FP with a smoother effect (here model 5), which increased the fraction of the variability in the data explained by model slightly and slightly improved the residuals, but gives no direct estimate of the FP effect on the dependent variable. The models have also been tested with interaction between factors (models 6, 6c, 10, 10b, 11, 13). Interactions were especially observed between hydrographical parameters, and between sediment types, seasons and FP. As expected there were interactions between the hydrographical parameters and depth and, accordingly, the model has also been tested with depth (model 4), and the individual hydrographical parameters separately (models 3a-3d) besides with all hydrographical parameters together (all models except 3 and 4). Seasonal differences were also tested in all models except models 1, 3 and 4.

**Results**

*Initial correlation plot analyses using merged datasets*

The results from the two-way correlation analyses exemplified in Figure 3 show that there generally is a small but significant negative correlation between FP and N, while there initially seems to be a very small and less significant positive correlation between FP and BD when including season in the two-way analyses (Fig. 3). When excluding season in the two-way correlation analyses, there is a small but highly significant negative correlation between FP and BD (not shown). This should be seen in context of a strong correlation between FP and season of year (as well as in relation to hydrographical factors and depth) with highest FP in the third quarter of the year compared to the second quarter. Strong correlations between FP and hydrographical factors are observed, i.e. the lower minimum temperature (t-min) the higher FP, and the higher minimum oxygen concentration (o-min) the higher FP.

Furthermore, there are observed strong correlations between the habitats/sediment types and the hydrographical factors as well as depth. There are as expected observed significant correlations between hydrographical features and depth, i.e. a positive correlation between depth and maximum current speed, minimum bottom salinity and also sediment type, while there is a negative correlation between depth and minimum bottom temperature and minimum bottom oxygen concentration. This is consistent with the bottom inflow of colder and more saline water into the Baltic from the North Sea and outflow of warmer and less saline surface water from the Baltic. A significant negative correlation between N and depth is observed while there is a positive correlation between depth and BD (see reasoning above). Finally, but very important there is observed a strong positive correlation between BD and N per sample. Consequently, it is important to take the total number of individuals, N, into account in each sample when analyzing biodiversity, BD.

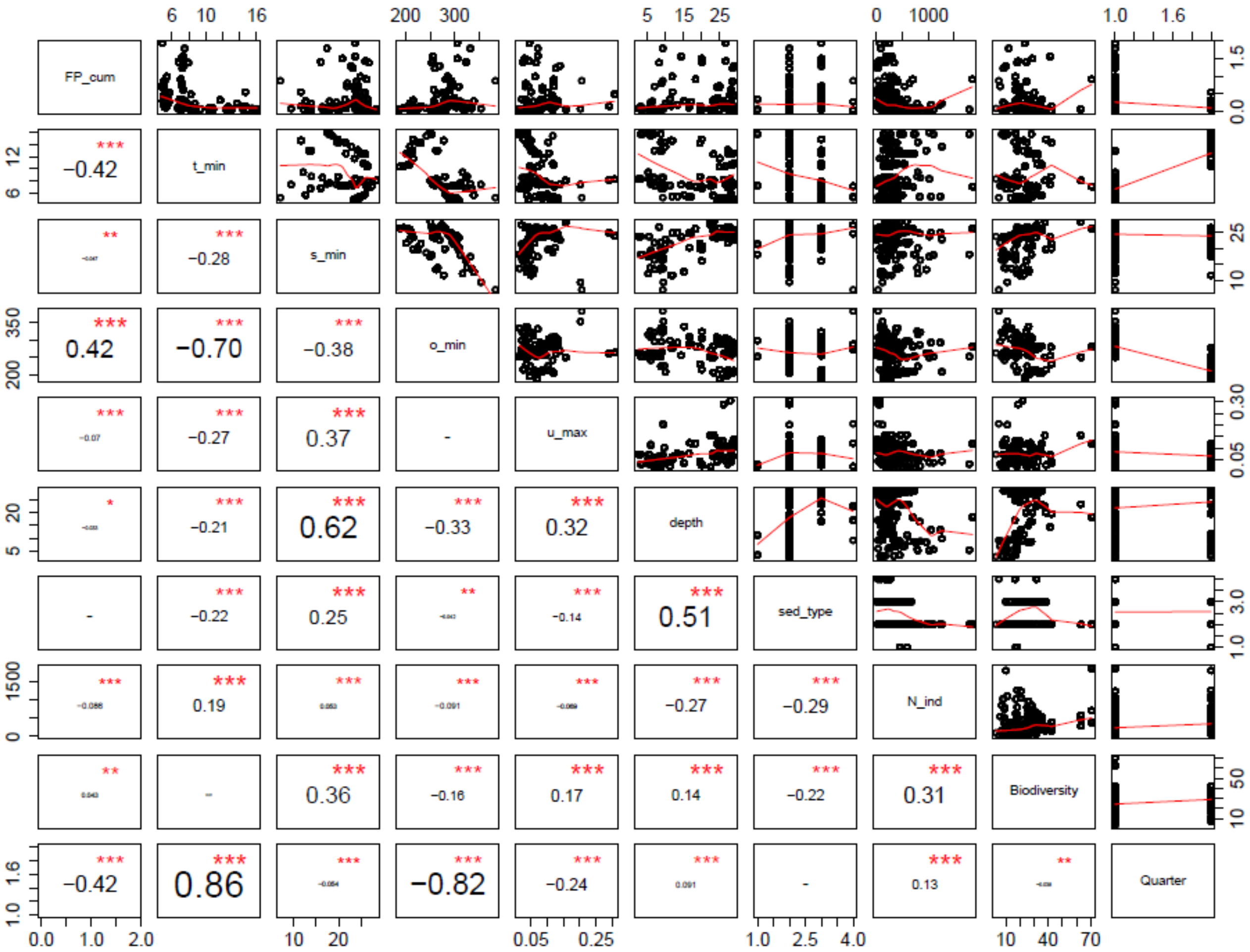


Figure 3. Two-way correlations between density, biodiversity, fishing pressure, temperature, salinity, oxygen, current speed, depth and sediment type.

When investigating the seasons separately (not shown), they basically show a negative correlation between FP and both N and BD, however, in the last season these negative correlations are smaller. When looking into the habitats separately (not shown), then a negative correlation between FP and both N and BD is observed for the habitats sublittoral mud and sublittoral mixed sediments. The sublittoral sand habitat has only few observations, and the results from here are therefore uncertain. For this habitat type, there is a positive correlation between BD and FP. It should be noted here that the season effect was not included when investigating the different habitat types separately. Accordingly, the initial two-way correlation analyses indicate that there are overall different trends and interactions in the impacts of FP on N and BD according to the different sediment types and the seasons of year, and at the same time strong correlations between some hydrographical parameters and FP, which complicate analyses of FP impacts on benthic invertebrates in general. Consequently, multivariate analyses of variance are needed to further explore the impacts and patterns herein.

The same type of two-way correlation analyses were made for selected single species where the relationship between N and B per sample and the FP as well as the hydrographical parameters have been initially investigated. The results are in general consistent that there is a negative relationship between FP and both N and B (not shown here).

*Results of the statistical modelling and multi-variate analysis of variance*

The Baseline model 2 analyses BD under consideration of N and all hydrographical factors, FP (without smoother) and the 3 sediment types (Table 4). It explains more than 84% of the variability in the data, and there are no significant trends in the residuals analyses (Fig. 4). The results show that N and FP highly significantly impacts BD; the higher N the higher BD, and the higher FP the lower BD (Table 4). Model 1 gives the same analysis as model 2 except it does not include season. The results of the analyses with the two models are very similar with respect to significance levels and tendencies in the impacts of the explanatory variables on BD, as well as with respect to the level of variability in the data explained by the model, except that N is not as highly significant in model 2 when including season compared to model 1. Furthermore, the residuals perform slightly better in model 2 (Fig. 4) compared to model 1. Accordingly, the impact of the density N on the BD is to some extent dependent on the season of year. From the analyses considering only main effects (Table 3) the above significance levels and tendencies with respect to impacts of the explanatory variables on BD are consistent (models 1-6). All these models analyzing BD also explain a very high proportion of the variability in the data ranging from 82% to nearly 90%.

There is a significant habitat type and according spatial effect on BD. The main effects models 1, 2 and 5 show that BD is significantly different at different habitats with a clear tendency towards higher diversity at more mixed and course sediment types and lower biodiversity at the more fine grained and soft sediment types. When running the models with each of the hydrographical factors isolated (models 3a-3d) or with depth instead of the hydrographical factors included (model 4) the tendency in the impact of sediment type 1 and 2 relative to sediment type 3 reverses from negative to positive impact on BD except for when running with current speed alone (model 3a). This indicates interactions between the impacts of hydrographical factors and of sediment types on BD. Similar, there appears to be a strong seasonal difference in the BD (models 2, 5 and 6) with tendency to significantly higher BD in third quarter compared to the second quarter of the year.

Furthermore, a highly significant impact of all tested hydrographical factors on the BD was observed when running the main effects models (models 1-3 and 5). The lower the current speed or the lower the minimum temperature or the lower minimum oxygen concentration the lower the BD, while the higher minimum salinity the higher BD. These tendencies and significance levels are consistent when running the model with each of the hydrographical factors separately (models 3a-3d), except for minimum temperature, where the tendency in the impact on BD reverses to result in slightly higher BD when the minimum temperature increases. Accordingly, there are interactions in the impacts of the hydrographical factors on BD.

Table 4. Results, parametric coefficients, and estimates of the statistical analyses with model 1.

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Family: Negative Binomial(3971654.157)     Link function: log
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*Parametric coefficients*

| | Estimate | Std Error | z value | p value | sign. level |
|---|---|---|---|---|---|
| (Intercept) | 4.4853473 | 0.2026668 | 22.131637 | 0.0000000 | *** |
| N_ind | 0.0000392 | 0.0000105 | 3.716180 | 0.0002023 | *** |
| FP_cum | -0.0600649 | 0.0115016 | -5.222296 | 0.0000002 | *** |
| t_min | -0.0352710 | 0.0038172 | -9.240099 | 0.0000000 | *** |
| s_min | 0.0155273 | 0.0027657 | 5.614210 | 0.0000000 | *** |
| o_min | -0.0038155 | 0.0003435 | -11.107494 | 0.0000000 | *** |
| u_max | -2.3415787 | 0.0996879 | -23.489093 | 0.0000000 | *** |
| sed_type1 | -0.0771912 | 0.0145254 | -5.314228 | 0.0000001 | *** |
| sed_type2 | -0.1439642 | 0.0338675 | -4.250810 | 0.0000213 | *** |

*Approximate significance of smooth terms*

| | Edf | Ref df | Chi square | p value | sign. level |
|---|---|---|---|---|---|
| s(YEAR) | 0.0000388 | 1.00000 | 8.981300e-03 | 0 | *** |
| te(lon,lat) | 23.4985121 | 23.89472 | 1.297017e+04 | 0 | *** |

| Variable | value |
|---|---|
| n | 4783 |
| Deviance explained | 84.4% |
| R-sqr (adj) | 0.88 |
| -REML | 14629 |
| Scale est. | 1 |

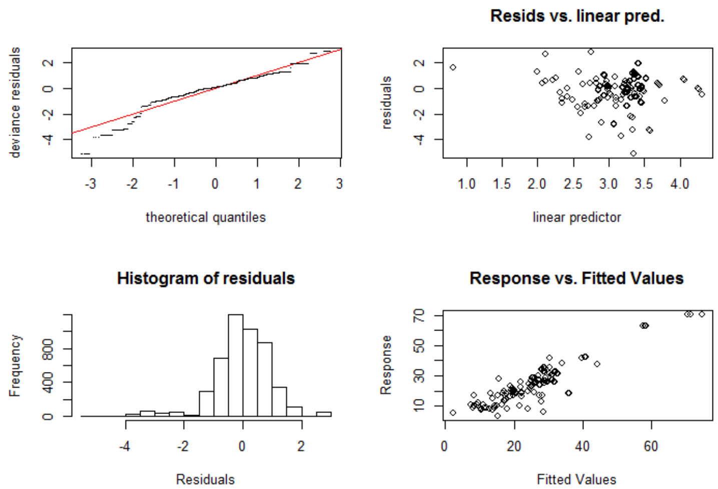


Figure 4. Residuals analysis of the model 1 statistical analyses.

Table 5. Results, parametric coefficients, and estimates of the statistical analyses with model 2.

```
Family: Negative Binomial(2596392.936)       Link function: log
```

*Parametric coefficients*

| | Estimate | Std Error | z value | p value | sign. level |
|---|---|---|---|---|---|
| (Intercept) | 4.1367077 | 0.2042790 | 20.250283 | 0.0000000 | *** |
| N_ind | 0.0000224 | 0.0000107 | 2.100907 | 0.0356491 | * |
| FP_cum | -0.0548631 | 0.0115388 | -4.754665 | 0.0000020 | *** |
| t_min | -0.0641759 | 0.0044540 | -14.408511 | 0.0000000 | *** |
| s_min | 0.0145931 | 0.0027577 | 5.291835 | 0.0000001 | *** |
| o_min | -0.0018632 | 0.0003765 | -4.948767 | 0.0000007 | *** |
| u_max | -2.3535675 | 0.1000614 | -23.521225 | 0.0000000 | *** |
| sed_type1 | -0.0692668 | 0.0145429 | -4.762925 | 0.0000019 | *** |
| sed_type2 | -0.1725488 | 0.0343107 | -5.029002 | 0.0000005 | *** |
| QuarterQ3 | 0.3519298 | 0.0281237 | 12.513659 | 0.0000000 | *** |

*Approximate significance of smooth terms*

| | Edf | Ref df | Chi square | p value | sign. level |
|---|---|---|---|---|---|
| s(YEAR) | 0.0000244 | 1.00000 | 2.24880e-03 | 0 | *** |
| te(lon,lat) | 23.5128001 | 23.90076 | 1.27908e+04 | 0 | *** |

| Variable | value |
|---|---|
| n | 4783 |
| Deviance explained | 84.9% |
| R-sqr (adj) | 0.88 |
| -REML | 14552 |
| Scale est. | 1 |

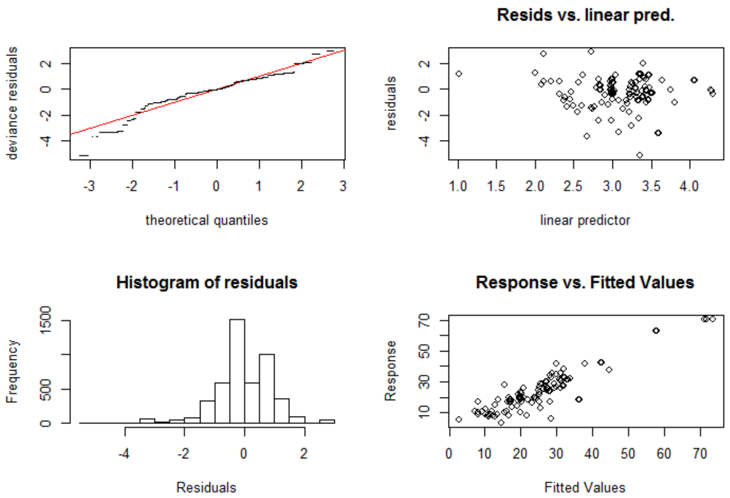


Figure 5. Residuals analysis of the model 2 statistical analyses.

Finally, the depth factor is highly significant, i.e. the higher depth the lower BD. This should also be seen in context of the higher depth the higher FP as well as in relation to the adverse strong correlations between hydrographical factors and depth described previously in the two-way correlation analyses.

It appears that the variability explained in the data by the model decreases significantly when not considering density, N, both without and with smoother on FP to levels around 60% (not shown).

When including interaction effects between FP, sediment type and season (model 6 full interaction model and model 6c reduced interaction model) and keeping all hydrographical factors in then not much more of the variability in the data is explained (86%; Table 3), and the residuals only improve slightly (Fig. 6). The tendencies in the impacts of the different explanatory variables on BD are the same, however, in this model N is only slightly significant, oxygen is not significant, and FP as main effect is only slightly significant (Table 6). Furthermore, the tendency in the BD on sediment type 2 (sand) reverses. However, there are significant interaction effects between FP and the sediment types and between FP and season. This strongly indicates that FP has different impacts on BD in different habitats dependent on season of year.

The use of a smoother on the FP (model 5) results in a relatively small increase in the proportion of the variability in the data explained by the model, and the tendencies are the same according to all the explanatory factors (not shown). The residuals perform equally well. However, this model does not provide estimates of the FP impact on BD.

Table 6. Results, parametric coefficients, and estimates of the statistical analyses with model 6c.

```
Family: Negative Binomial(2943758.108)       Link function: log
```

*Parametric coefficients*

| | Estimate | Std Error | z value | p value | sign. level |
|---|---|---|---|---|---|
| (Intercept) | 3.3609350 | 0.1481739 | 22.682366 | 0.0000000 | *** |
| N_ind | 0.0000254 | 0.0000106 | 2.385396 | 0.0170608 | * |
| t_min | -0.0537990 | 0.0039570 | -13.596061 | 0.0000000 | *** |
| s_min | 0.0194000 | 0.0026738 | 7.255661 | 0.0000000 | *** |
| u_max | -1.4188689 | 0.1286084 | -11.032477 | 0.0000000 | *** |
| FP_cum | -0.0357849 | 0.0168840 | -2.119461 | 0.0340515 | * |
| sed_type1 | -0.0886200 | 0.0152481 | -5.811887 | 0.0000000 | *** |
| sed_type2 | 0.4766472 | 0.0827628 | 5.759198 | 0.0000000 | *** |
| QuarterQ3 | 0.6201923 | 0.0294334 | 21.071054 | 0.0000000 | *** |
| FP_cum:sed_type1 | -0.0369840 | 0.0188852 | -1.958359 | 0.0501879 | . |
| FP_cum:sed_type2 | -2.5284248 | 0.3366874 | -7.509710 | 0.0000000 | *** |
| FP_cum:QuarterQ3 | -2.3205356 | 0.1453161 | -15.968885 | 0.0000000 | *** |

*Approximate significance of smooth terms*

| | Edf | Ref df | Chi square | p value | sign. level |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| s(YEAR) | 0.0000243 | 1.00000 | 2.687500e-03 | 0 | *** |
| te(lon,lat) | 23.5974931 | 23.93224 | 1.282503e+04 | 0 | *** |

| Variable | value |
|---|---|
| n | 4783 |
| Deviance explained | 86% |
| R-sqr (adj) | 0.89 |
| -REML | 14409 |
| Scale est. | 1 |

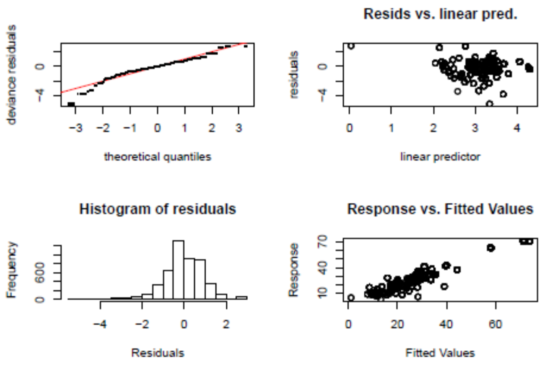


Figure 6. Residuals analysis of the model 6c statistical analyses.

Table 7. Results, parametric coefficients, and estimates of the statistical analyses with model 10b.

```
Family: Negative Binomial(4.089)          Link function: log
```

*Parametric coefficients*

| | Estimate | Std Error | z value | p value | sign. level |
|---|---|---|---|---|---|
| (Intercept) | -1.4450011 | 0.3235562 | -4.4659970 | 0.0000080 | *** |
| s_min | 0.0959594 | 0.0064149 | 14.9589353 | 0.0000000 | *** |
| o_min | 0.0196826 | 0.0007942 | 24.7820379 | 0.0000000 | *** |
| u_max | -6.4078272 | 0.2788568 | -22.9789203 | 0.0000000 | *** |
| FP_cum | -0.3195826 | 0.0431567 | -7.4051706 | 0.0000000 | *** |
| sed_type1 | -0.5326537 | 0.0382581 | -13.9226407 | 0.0000000 | *** |
| sed_type2 | -1.3035712 | 0.1544145 | -8.4420266 | 0.0000000 | *** |
| QuarterQ3 | 1.9357904 | 0.0713607 | 27.1268551 | 0.0000000 | *** |
| FP_cum:sed_type1 | 0.2749942 | 0.0467778 | 5.8787332 | 0.0000000 | *** |
| FP_cum:sed_type2 | 0.4275921 | 0.5533748 | 0.7726988 | 0.4397007 | |
| FP_cum:QuarterQ3 | -1.2290742 | 0.3773108 | -3.2574581 | 0.0011241 | ** |

*Approximate significance of smooth terms*

| | Edf | Ref df | Chi square | p value | sign. level |
|---|---|---|---|---|---|
| s(YEAR) | 0.0000019 | 1.00000 | 0.0001699 | 0 | *** |
| te(lon,lat) | 23.2488984 | 23.78735 | 3810.6623829 | 0 | *** |

| Variable | value |
|---|---|
| n | 4783 |
| Deviance explained | 60.5% |
| R-sqr (adj) | 0.52 |
| -REML | 30128 |
| Scale est. | 1 |

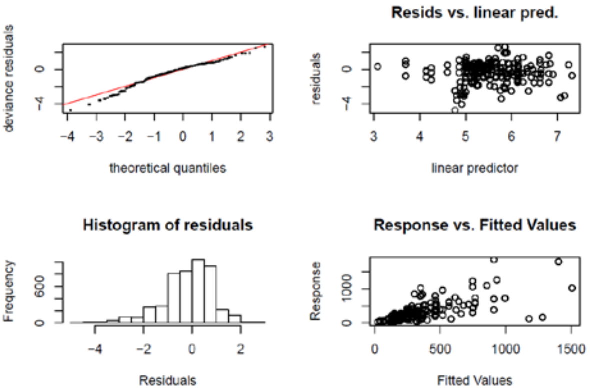


Figure 7. Residuals analysis of the model 10b statistical analyses.

The analyses of density, N, alone (models 7 and 10 and 10b), show that FP is highly significantly impacting density with same tendency as for BD, i.e. the higher FP the lower density (Table 7). This is the case both for the main effect model 7 as well as the interaction models 10 and 10b. Also similar tendencies and significance levels are observed for the influence of the other explanatory variables on N as for BD, except for minimum oxygen where the tendency reverses. However, the deviance in the data explained is less (around 60%; Table 3) when analyzing density, and the residuals do not perform better (Fig. 7) compared to the BD analyses. Similar to BD then inclusion of first order interaction effects between FP, sediment type, and season in the analyses of impact on N does not increase the model explanation of the variability in data much (61%; Table 3). When including the interactions, the explanatory variables show the same significance levels and tendencies and also significance of the same interaction effects. The tendency in the interaction effect between FP and season is the same as for BD, however, the tendency in the interaction effect between fishing pressure and habitat type (sediment type) reverses compared to when analyzing for BD. Also when analyzing invertebrate density, the results on impacts of fishery strongly indicates that the FP has different impacts on the density in different habitats dependent on season of year.

The analyses of biomass, B, (models 8, 9 and 11) show that models with biomass as the dependent variable does not explain more than 7% of the variability in the data (model 8), and this does not improve when analyzing B given N (model 9) or when including interaction effects between FP, sediment type and season. Furthermore, the analyses of B in all those models show strong residual trends.

When analyzing individual mean weight in the benthic invertebrate community, i.e. B/N as the dependent variable (models 12 and 13) the results again show that FP has a highly significant impact on the benthic community (Table 8) with same tendency as for the BD and density indicators. That is, the higher FP the lower individual mean weight of the organisms in the benthic community (Table 8). For this dependent variable, the model again explains only around 60% of the variability in data (Table 3) similar to the analyses of density as the dependent variable, which also is a part of the B/N variable. The residuals perform reasonably well also for the individual mean weight analyses (Fig. 8). There are significant interaction effects for B/N, however, they are difficult to interpret as the interactions both in N and B are in effect here, which make conclusions on this rather difficult. Similar, conclusions on the tendencies in the main effects of the hydrographical explanatory variables for this dependent variable shall be taken with caution because they are influenced on main effects both on the biomass and the density variables.

Table 8. Results, parametric coefficients, and estimates of the statistical analyses with model 13.

```
Family: Tweedie(p=1.961)            Link function: log
```

*Parametric coefficients*

| | Estimate | Std Error | z value | p value | sign. level |
|---|---|---|---|---|---|
| (Intercept) | 14.6969591 | 0.6058564 | 24.2581556 | 0.0000000 | *** |
| s_min | -0.2557078 | 0.0124463 | -20.5448240 | 0.0000000 | *** |
| o_min | -0.0385642 | 0.0015278 | -25.2424096 | 0.0000000 | *** |
| u_max | 1.4845123 | 0.5261805 | 2.8212987 | 0.0048028 | ** |
| FP_cum | -0.6084706 | 0.0840787 | -7.2369184 | 0.0000000 | *** |
| sed_type1 | 0.1716287 | 0.0930590 | 1.8442999 | 0.0652017 | . |
| sed_type2 | -1.2861986 | 0.2954591 | -4.3532211 | 0.0000137 | *** |
| QuarterQ3 | -2.6023093 | 0.1520420 | -17.1157221 | 0.0000000 | *** |
| FP_cum:sed_type1 | 0.5567751 | 0.0936523 | 5.9451297 | 0.0000000 | *** |
| FP_cum:sed_type2 | -8.2898458 | 1.0501411 | -7.8940302 | 0.0000000 | *** |
| FP_cum:QuarterQ3 | -5.0112304 | 0.9323200 | -5.3750110 | 0.0000001 | *** |
| sed_type1:QuarterQ3 | -0.4660720 | 0.1722162 | -2.7063190 | 0.0068277 | ** |
| sed_type2:QuarterQ3 | 0.0000000 | 0.0000000 | NaN | NaN | |
| FP_cum:sed_type1:QuarterQ3 | 0.9110333 | 1.8162628 | 0.5015977 | 0.6159738 | |
| FP_cum:sed_type2:QuarterQ3 | 0.0000000 | 0.0000000 | NaN | NaN | |

*Approximate significance of smooth terms*

| | Edf | Ref df | Chi square | p value | sign. level |
|---|---|---|---|---|---|
| s(YEAR) | 0.0000005 | 1.00000 | 0.0000339 | 0 | *** |
| te(lon,lat) | 23.5663625 | 23.91066 | 218.5251432 | 0 | *** |

| Variable | value |
|---|---|
| N | 4783 |
| Deviance explained | 59.5% |
| R-sqr (adj) | 0.46 |
| -REML | -6852 |
| Scale est. | 0.787718551155899 |

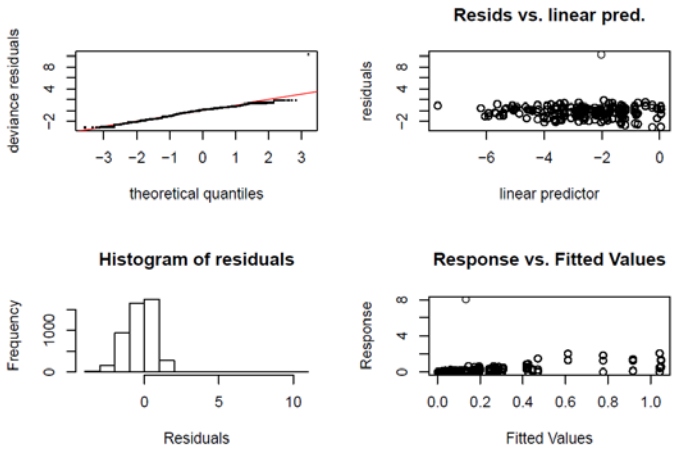


Figure 8. Residuals analysis of the model 13 statistical analyses.

## Conclusions

Overall, the results indicate that biodiversity and density and mean weight are rather strong indicators for impacts of fishery on the benthic invertebrate community with respect to different levels of fishing intensity, while benthic invertebrate biomass seems not to be a strong indicator on community level in this respect. The latter naturally also influences the mean weight (B/N) indicator. It is evident that there are strong and significant interaction effects and that the FP has different impacts on the biodiversity and density in different habitats dependent on season of the year. Overall, it seems that the impacts of fishing pressure on the benthic community biodiversity and density and mean weight in the benthic community is in the same order of magnitude as the influence of natural hydrographical factors, e.g. current speed. Also, it is evident that the positive correlation and impact of density on biodiversity needs to be taken into consideration when evaluating impacts on biodiversity.

The above results suggest that we can reject all the 0-hypotheses listed in the introduction, however, more analyses are necessary, among other on selected single species, to finally conclude on this. Furthermore, future analyses will involve the longevity indicator as well. Finally, it will be an advantage to describe into detail the potential processes, i.e. the causality in the observed results, for the impacts of the hydrographical factors on the biodiversity, density and individual mean weight in the benthic community.

## References

Bastardie, F., Nielsen, J.R., Ulrich, C., Egekvist, J., and Degel, H. 2010. Detailed mapping of fishing effort and landings by coupling fishing logbooks with satellite-recorded vessel geo-location. Fish. Res. 106: 41-53 pp. doi:10.1016/j.fishres.2010.06.016.

Bates, D., Maechler, M., Bolker, B. & Walker, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Eigaard, O.R., Bastardie, F., Breen, M., Dinesen, G.E., Hintzen, N.T., Laffargue, P., Mortensen, L.O., Nielsen, J.R., Nilsson, H.C. O'Neill, F.G. Polet, H., Reid, D. G. Sala, A. Sköld, M., Smith, C., Sørensen, T. K., Tully, O., Zengin, M., Rijnsdorp A. D. 2016a. Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. ICES Journal of Marine Science; doi:10.1093/icesjms/fsv099E.

Eigaard O.R., Bastardie F., Hintzen N., Buhl-Mortensen L., Buhl-Mortensen P., Catarino R., Dinesen G.E., Fock H., Geitner K., Gerritsen H., Gonzalez M.M., Jonsson P., Kavadas S., Lafargue P., Lundy M., Mirelis G.G., Nielsen J.R., Papadopoulou N., Posen P., Pulcinella J., Russo T., Sala A., Silva C., Smith C., Vanelslander B., Zengin M., Rijnsdorp, A.D. 2016b. Benthic impact of fisheries in European waters: the distribution and intensity of bottom trawling. (In Press ICES J. Mar. Sci.).

Hintzen, N. T., Bastardie, F., Beare, D., Piet, G.J., Ulrich, C., *et al.* 2012. VMStools: Open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data. Fisheries Research, 115: 31–43.