Developing a statistical model to predict the ecological benthic state in the Dutch coastal zone in relation to shrimp fisheries and closed areas

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Wageningen Marine Research

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Contents

Summary

The ‘VIBEG’ agreement regulates fishery in the Natura 2000 areas ‘Noordzeekustzone’ and ‘Vlakte van de Raan’, in which a number of areas are closed completely to all bottom-contacting fisheries. In this report we develop an instrument to quantify the ecological benefits of closed areas for the state of the seafloor in the Dutch coastal zone, with a particular focus on shrimp fisheries in the ‘Noordzeekustzone’. The method relies on a statistical relationship between the longevity distribution of the local benthic invertebrate fauna, the bottom trawling intensity and habitat conditions. Such a relationship has been estimated for offshore benthic communities in the North Sea, but not for coastal communities in particular. With the relationship, the Relative Benthic State (RBS) can be estimated, which represents the extent to which the benthos community is impacted by trawling compared to a state of no trawling impact. The RBS is calculated for two simulated fishing regimes; one under the current VIBEG situation (as from 2013 onwards) in the ‘Noordzeekustzone’ as well as for a proposed modification of the VIBEG closed areas. This modification was the result of new negotiations between the VIBEG parties, initiated because the first zoning scheme was seen as too restrictive by the fishery. The method takes into account both the effect of reduced fishing by vessels targeting shrimp in the closed areas, but also that of the predicted displacement of fishing effort to areas which remain open to shrimp fishing.

Biomass data from benthic macrofauna were obtained from the MWTL monitoring programme on the Dutch continental shelf. Only samples from within the 12 nautical-miles zone were selected. The biomass data by taxon were combined with information on longevity of each taxon and converted to cumulative proportional biomasses per longevity class per sample, i.e. the longevity composition. For each sampling location, the corresponding trawling frequency by shrimp trawlers was calculated based on VMS data and logbook information. Several variables were obtained to reflect the habitat where benthos samples were collected, including depth, mud, gravel, silt, wind and tidal and orbital velocity.

The longevity composition of the benthos samples from the Dutch coastal zone was modelled against shrimp trawling frequency and habitat variables using linear mixed models, with sampling station and sampling year as random effects. A range of models with different variable configurations were set up. The Akaike Information Criterion and a cross-validation procedure were used to identify the best fitted and predictive model. The final model was constructed using INLA to enable the inclusion of spatio-temporal varying random effects as to improve the prediction of the Relative Benthic State. This model, together with predictions of fishing effort, was used to calculate the RBS in the current and new VIBEG situation.

The final longevity composition model indicated that more frequently trawled areas or areas with a higher orbital velocity were inhabited by communities with relatively high proportional biomasses of long-lived species. This goes against the expectation that long-lived species are most vulnerable to disturbance due to their low recovery rate. Yet, similar relationships have been observed in previous studies. Explanations could be that these particular long-living species have other traits that make them less vulnerable to disturbance, e.g. being able to burrow quickly and deeply to avoid disturbance, or a hard shell that protects them against physical disturbance.

Other important variables for predicting the longevity composition were depth and gravel. The model suggested that deeper waters in the Dutch coastal zone consist of communities with a higher proportional biomass of long-lived species than in more shallow waters. Although gravel content in the Dutch coastal zone is generally low compared to more offshore waters in the North Sea, it was found that areas with very low gravel content were inhabited by communities with a lower proportional biomass of long-lived species than in areas with higher gravel content.

Although the model generally fitted well to the observed benthos community data, it struggled with extremely low or high biomass values (i.e. one longevity class having either very low or very high biomass). Further model development is therefore needed.

The predicted change in distribution of fishing effort in the new VIBEG situation led to a minor improvement of the overall Relative Benthic State (i.e. impact of the benthic community by trawling) in the 'Noordzeekustzone' compared to the current VIBEG situation. The RBS slightly improved in the north-eastern part and slightly declined in the southwestern part.

Interestingly, the longevity model indicated that higher trawling intensity was associated with a higher proportion of long-lived biomass. Conceptually, trawling is generally associated with more short-lived species, as these are quicker to recover after disturbance. This assumption is also embedded in the calculation of the relative benthic state. The mechanisms potentially underlying the positive empirical relationship we obtained are not included in the RBS method. That means that while RBS is still an appropriate indicator for the degree of disturbance induced by trawling, it should not be used as a prediction of actual benthic biomass in the system.

1 Introduction

In 2011, the 'VIBEG' agreement was signed. This agreement regulates fishery in the Natura 2000 areas 'Noordzeekustzone' and 'Vlakte van de Raan' and entered into force in 2013. As part of this agreement, a number of areas were closed completely to all bottom-contacting fisheries (so-called Zone-I areas). Closing areas to fisheries potentially incurs an economic cost to the fishers operating in the area. In order for politicians and policymakers to weigh this cost against the benefits of the closures, it is important to quantify these benefits. In this report we develop an instrument to perform this quantification and apply it to two simulated fishing regimes. We make use of a general method for quantifying the effects of trawl fisheries on the seafloor, which has been widely used in recent years (Bastardie *et al.*, 2020; Hamon *et al.*, 2020; Rijnsdorp *et al.*, 2020; Van Denderen *et al.*, 2020; Hintzen *et al.*, 2021; ICES, 2022). This method relies on a statistical relationship between the longevity distribution of the local benthic invertebrate fauna and the bottom trawling intensity, and the bulk of this study is concerned with deriving this relationship for the area we are interested in – the Dutch coastal area. With the relationship, the Relative Benthic State (RBS) can be estimated that represents the extent to which the benthos community is impacted by trawling compared to a state of no trawling impact.

The derived relationship and the general method to estimate the RBS are applied to shrimp fisheries in the 'Noordzeekustzone' as a case study. The RBS is estimated for two simulated fishing situations (Figure 1.1):

- Status quo based on the current VIBEG zone-I areas (since 2013) within the 'Noordzeekustzone' (Staatscourant, 2013);
- Revision of the configuration of the VIBEG zone-I areas based on re-negotiation of stakeholders (currently in the process of being closed on EU-level through the CFP regulations). This revision was the result of new negotiations between the VIBEG parties, initiated because the first zoning scheme was seen as too restrictive by the fishery.

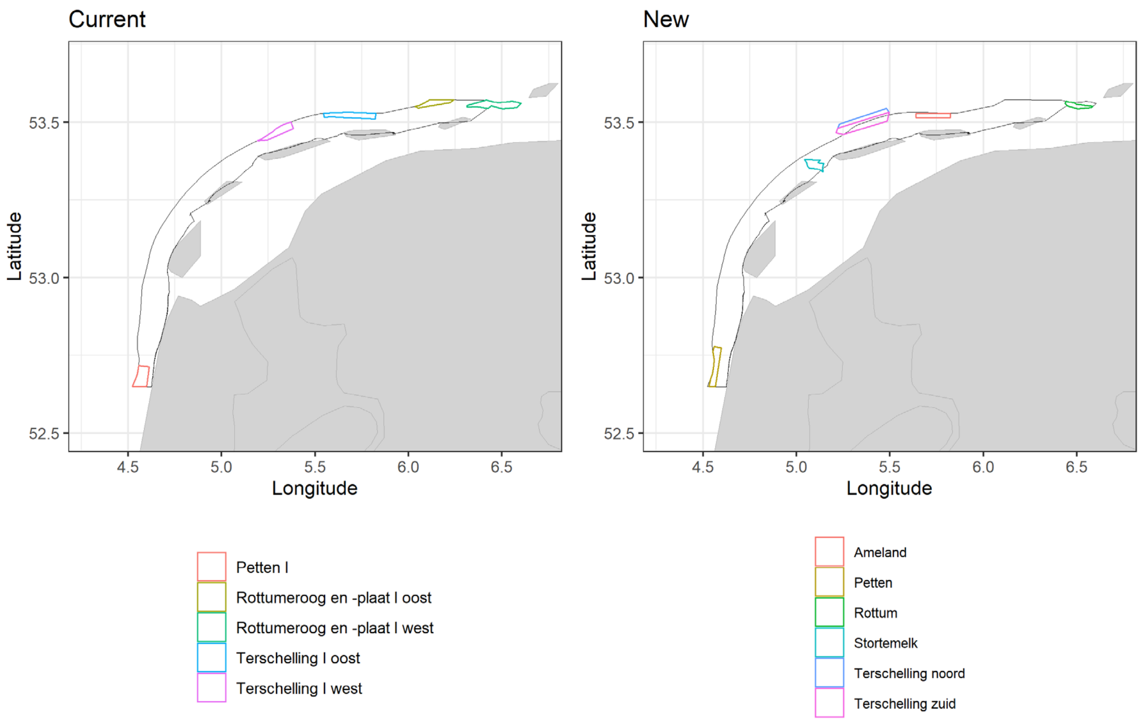

Figure 1.1 *The 'Noordzeekustzone' (black line), and the current and new VIBEG zone-I areas.*

2 Materials and Methods

The methodology and data use are first briefly summarised here, and described in more detail in the sections thereafter.

A statistical model was constructed that models the longevity composition of benthic communities in the Dutch coastal zone using observed benthos samples, observed shrimp fisheries effort, and habitat variables. The input data were:

- Benthic biomass samples from the multi-year macrobenthos MWTL monitoring programme across the Dutch continental shelf. Only samples from the coastal zone were used.
- Longevity information of benthos from existing literature sources.
- Vessel monitoring system (VMS) and logbook data of Dutch shrimp fishing vessels to calculate shrimp fishing effort at the location and year prior to sampling the benthos.
- Habitat information at the location and the time of the benthic sampling – collected from existing databases and literature sources.

The constructed statistical model was applied, as part of the methodology to calculate the Relative Benthic State, to two situations for the 'Noordzeekustzone'. This area is one of the two Natura-2000 areas falling under the VIBEG agreement. One situation represents the status quo, whereas the other situation represents a new configuration of VIBEG areas within the 'Noordzeekustzone'. The main input data were:

- Simulated shrimp fishing effort for each VIBEG situation using a spatial fishing effort model.
- Habitat information across the 'Noordzeekustzone'.
- The constructed statistical model for the longevity composition of benthos. Together with the simulated fishing effort data and habitat information, the Relative Benthic State was predicted for the two VIBEG situations.

2.1 Data

2.1.1 Benthos samples

Biomass data were obtained from macrobenthos samples collected during the MWTL monitoring framework of the Dutch Ministry of Infrastructure and Water Management (Verduin and Leeuwis, 2013). The macrobenthos survey ran annually until 2010, after which sampling continued once every three years. To match fishing effort, available from 2002 onwards, benthos data from 2003-2010, 2012 and 2015 were selected. Only samples from within the 12-mile zone were selected (Figure 2.1), as shrimp fisheries mainly take place within the coastal zone. This led to 231 samples in total from 58 unique sampling stations (Table 2.1). Samples were taken from March to May with a Reineck box corer with a sampling surface area of 0.078 m^2 and flushed over a 1 mm mesh size sieve. Taxonomic identification was done at the species level whenever possible. The biomass per taxon in each sample was measured as the ash free dry weight in grams (g). Across all samples 244 taxa were reported, with the majority being at the species (182), genus (29) or family (14) level. The number of taxa per sample varied between 1 and 32.

Table 2.1
Number of sampling stations per year.

Year	Number of sampling stations
2003	16
2004	18
2005	20
2006	20
2007	20
2008	20
2009	20
2010	20
2012	20
2015	57

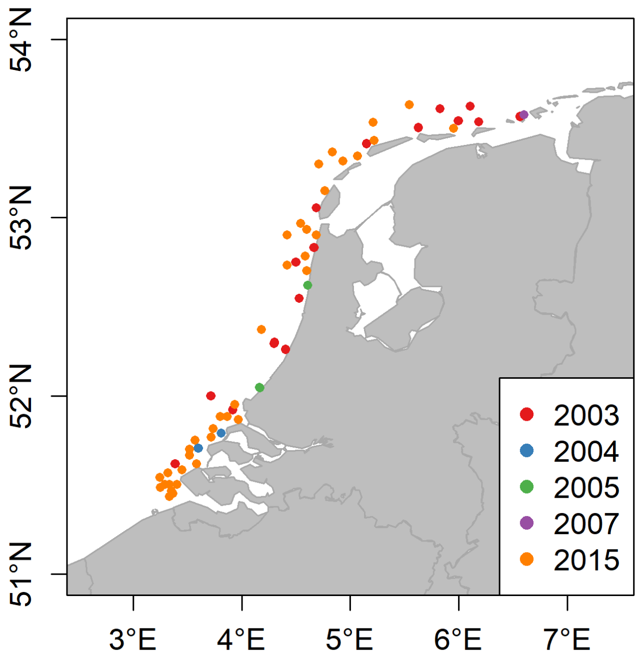

Figure 2.1 *Sampling stations of box corer samples in the MWTL macrobenthos survey. Colour indicates the starting year of sampling.*

2.1.2 Longevity

Information on longevity of taxa was derived from two sources (Bolam *et al.*, 2017; Beauchard *et al.*, 2021) that report longevity in four classes: <1 year, 1-3 years, 3-10 years and >10 years. The highest taxonomic resolution of Bolam *et al.* was genus, whereas this was species in Beauchard *et al.* The dataset of Bolam *et al.* was complemented with species-level taxa from Beauchard *et al.*, meaning that information on the species level was used when available. If there was no species-specific information for a species available, information at the genus level (from Bolam *et al.*) was used. Missing values for taxa for which neither dataset had information available at its corresponding taxonomic level, were derived from taxa within the same family or order. Thirteen taxa had to be excluded, as no longevity information could be assigned. In terms of biomass, these taxa together represented 0.28% of the total biomass across all samples. The final number of taxa used in the analysis was 231.

In the majority of samples, biomass was dominated by the 3-10 years longevity group, whereas the <1 year longevity group tended to have very low biomass (Figure 2.2). Biomass per longevity class within each sample was made cumulative, resulting in cumulative longevity classes of <1 year, <3 years and <10 years (Figure 2.2). Subsequently, these were made relative to the total biomass of each sample, resulting in a proportional biomass per cumulative longevity class. This will from here on be referred to as the 'longevity composition' of the benthic community.

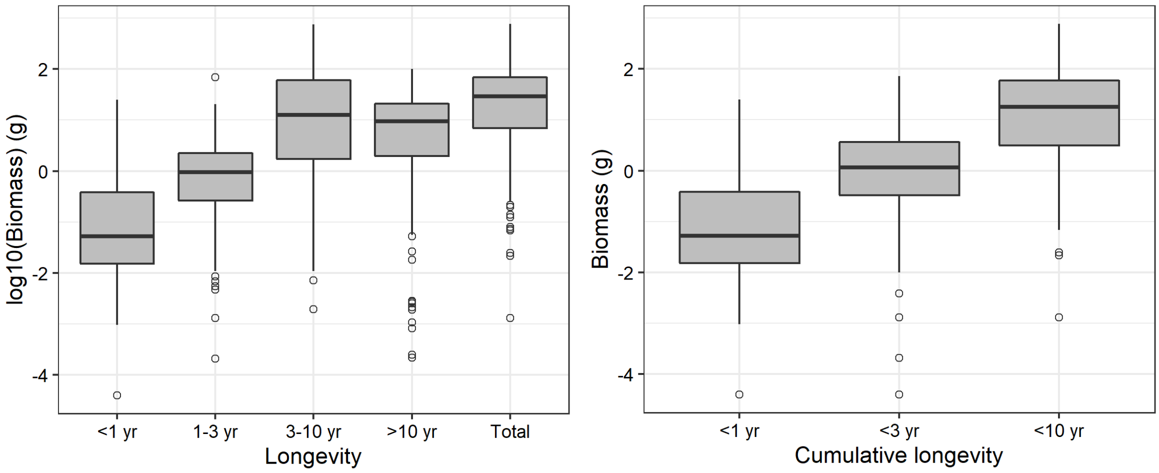

Figure 2.2 *Biomass per longevity group and total biomass (left figure) and biomass per cumulative longevity group (right figure). Biomass is plotted on a log10-scale.*

2.1.3 VMS and logbook data

Dutch VMS (Vessel Monitoring System) and logbook data from 2002 to 2015 were extracted for each grid cell from the VISSTAT database, and all records with shrimp fishing gear were selected. VMS data contain information on vessel speed and vessel position, whereas the vessel logbooks provide information on gear, vessel length and power (Hintzen *et al.*, 2012). Speed profiles were used to distinguish speeds into steaming, fishing and floating (Poos *et al.*, 2013). These were used to interpolate fishing tracks and to estimate the fishing effort per grid cell in the area trawled in km^2. All fishing effort within one year prior to sampling was summed across all vessels that had been active in that year and in that grid cell. This was done for each year of sampling separately. Finally, the surface Swept Area Ratio (SAR) was calculated as the total amount of surface trawled per year (in km^2) divided by the surface area of the grid cell (Eigaard *et al.*, 2016). This is the trawling frequency in $year^{-1}$ and was used in modelling the longevity composition (Figure 2.3).

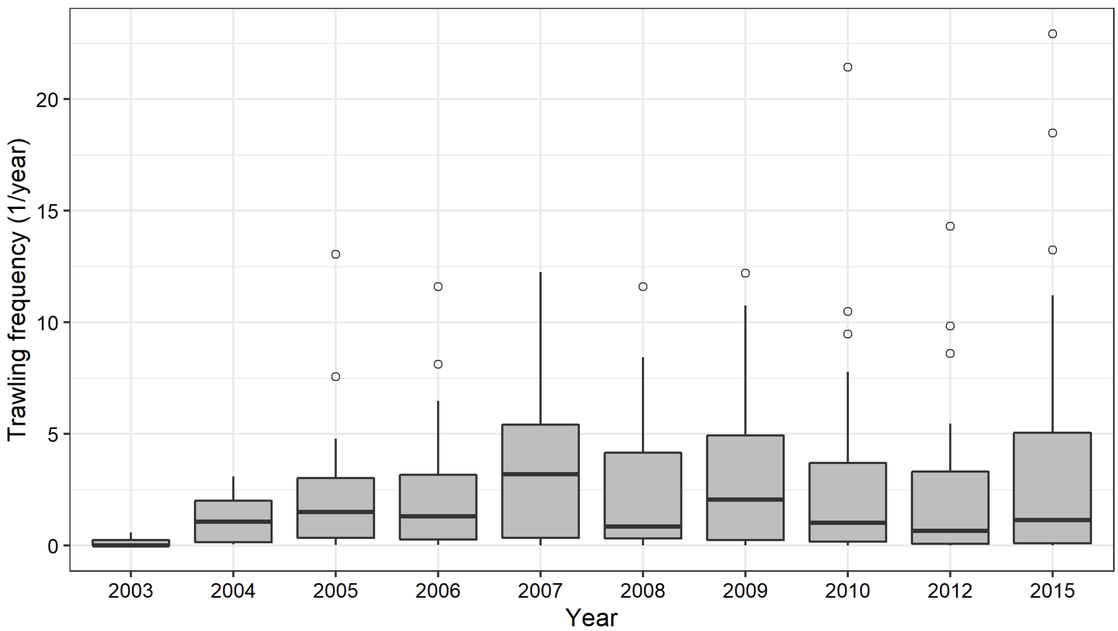

Figure 2.3 *Variation in trawling frequency ($year^{-1}$) of the Dutch shrimp fisheries in grid cells in which benthos sampling stations are located.*

2.1.4 Simulated fishing effort

In order to predict the benthic state for the two VIBEG situations, the fishing effort in both situations is required. Due to lack of VMS and logbook data of shrimp fisheries for the new situation, the fishing effort needs to be estimated for the new situation. As fishing effort under the current regime may vary largely between years and to make to comparison with the new situation more appropriate, the fishing effort for the current situation was estimated as well. A spatial fishing effort model (Wilkes *et al.* in prep) was therefore used to predict the number of fishing hours for both the current and new VIBEG situation. This model was constructed using VMS and logbook data from Dutch shrimp fisheries in the Dutch coastal zone from 2010 to 2020. It predicts the spatial effort of the fleet based on a set of input parameters, such as location, season, distance to nearest restricted area and type of restriction. For the current situation, it was assumed that not all fishermen respect the closed areas. For the new situation, it was assumed that all fishermen respect the closed areas. The total number of fishing hours in both situations was set to 63,406 hours, which is the value observed with VMS data for shrimp fishermen in the Dutch coastal zone in 2020 (Tony Wilkes, pers. comm.). Predicted fishing hours per grid cell were converted to SAR using a gear width of 18 m and by assuming an average fishing speed of 3 knots (Niels Hintzen, pers. comm.).

2.1.5 Habitat

A range of variables was selected to represent the habitat of the benthic community in the Dutch coastal zone. The type of sediment dominating the seabed has been found to influence the longevity composition in the North Sea (Rijnsdorp *et al.*, 2018). Rijnsdorp *et al.* (2018) observed that the benthos community shifted to longer-lived species when gravel was dominating, to shorter-lived species when mud was dominating, and to communities with an intermediate longevity in sandy sediments. Although the majority of the North Sea coastal zone consists of sand, there is variation in gravel and mud content, as well as in silt content. Silt, gravel and mud content is the percentage of the sediment that is composed of either silt, gravel or mud. Gravel and mud content were extracted from (Wilson *et al.*, 2018), whereas silt content was obtained from a monitoring programme of the seabed financed by the Dutch Ministry of Infrastructure and Environment I&M in 2006 (Figure 2.4).

Natural disturbance of the seabed can be caused by tides, waves and wind. Tidal bed shear stress has been found to shift the longevity composition towards shorter-lived taxa, and to make the negative impact of trawling weaker in areas with high shear stress (Rijnsdorp *et al.*, 2018). Here, mean tidal and orbital velocity (m/s) were used to represent the natural disturbance on the seabed caused by tides and waves, respectively (Wilson *et al.*, 2018) (Figure 2.4). Data on annual mean wind speed and the observed maximum wind speed (m/s) were also collected to explore the effect of wind speed as a proxy for natural disturbance. Wind speed might be of particular influence on benthic communities in shallow, coastal waters such as those studied here (Pérez Rodríguez and van Kooten, 2019). Three weather stations at the Dutch coast were selected – two on the mainland (Oosterschelde and IJmuiden) and one on the island of Vlieland. Data were obtained from the Royal Netherlands Meteorological Institute (https://www.knmi.nl/nederland-nu/klimatologie/daggegevens). Wind speeds from Vlieland were assigned to stations at 53 degrees latitude or higher, whereas averaged wind speeds from Oosterschelde and Ijmuiden were assigned to sampling stations south of 53 degrees latitude (Figure 2.5).

Water depth may be another determinant of the longevity composition of benthic communities, as many variables vary with depth, such as temperature, light, food supply and natural disturbance, with communities in deeper waters potentially being less exposed to tides and wind. Depth data were extracted from EMODnet (https://www.emodnet-bathymetry.eu/data-products).

As silt, gravel and mud content, and orbital and tidal velocity were not available for all sampling stations, three sampling stations were excluded from further analysis.

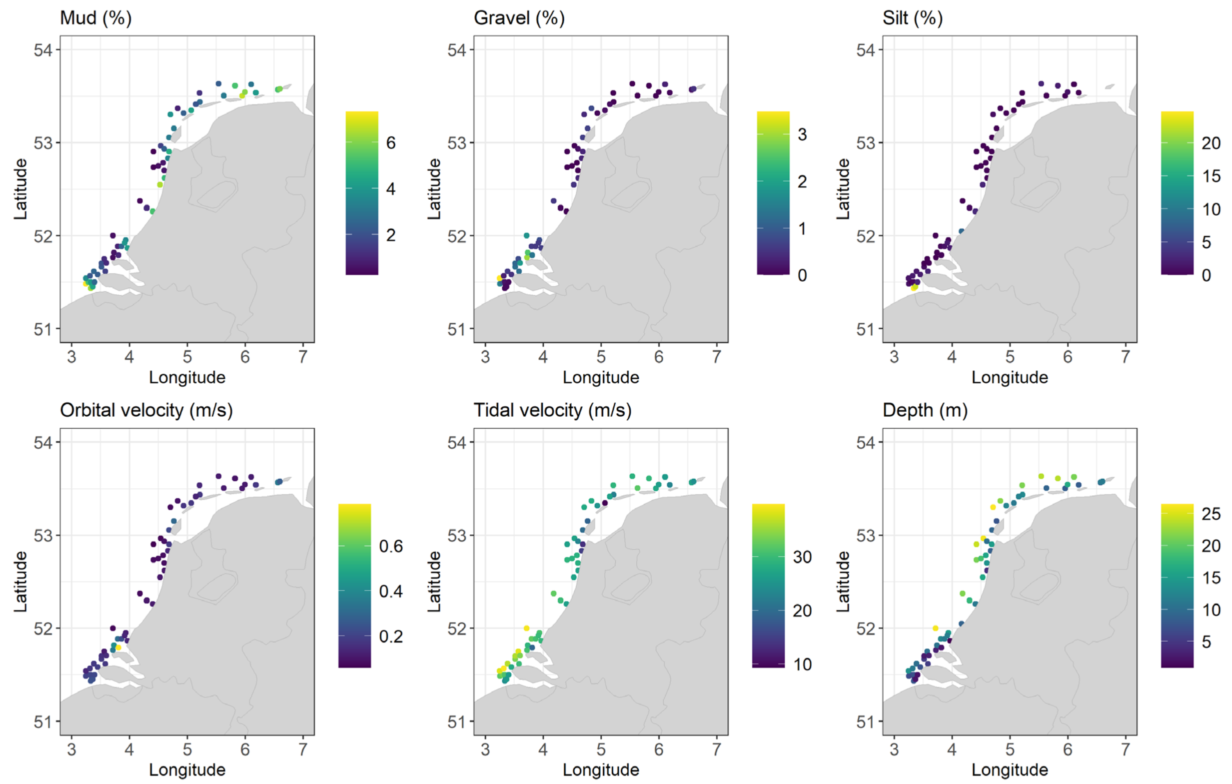

Figure 2.4 *Habitat variables at each benthos sampling location.*

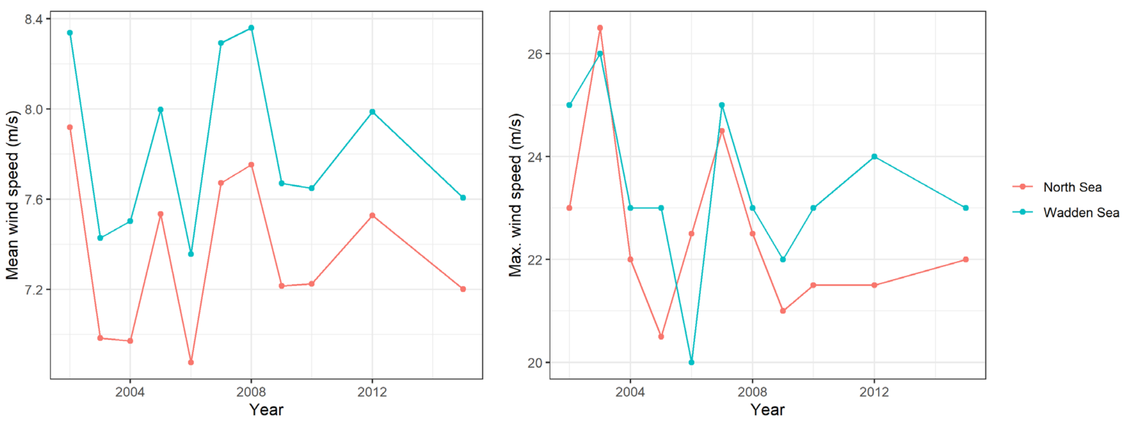

Figure 2.5 *Mean (left) and maximum (right) wind speed in the North Sea and Wadden Sea area.*

2.2 Modelling longevity composition

The longevity composition was modelled using linear mixed models. The response variable was the cumulative proportional biomass of each longevity class. These were transformed with a probit function, which is the quantile function of a normal distribution and commonly used in modelling proportional data. Before transforming, a small value was added to true zeroes in the dataset, and the same small value was subtracted from values of 1.

Longevity, trawling frequency and gravel content are three major known factors influencing the longevity composition (Rijnsdorp *et al.*, 2018), thus were included in the initial Linear Mixed Model:

$$probit\left(\frac{B_{ij}}{B_j}\right) \sim \beta_0 + \beta_1 \ln\left(L_{ij}\right) + \beta_2 sqrt\left(T_j\right) + \beta_3 G_{L,j} + \beta_4 G_{M-L,j} + \beta_5 G_{M,j} + \beta_6 G_{H,j} + \varepsilon_{ij} + Station_j + Year_j$$

$$Station_j \sim N(0, \sigma_s)$$

$$Year_j \sim N(0, \sigma_y)$$

where B_{ij} is the cumulative biomass of longevity class i (i in {1,3,10}) and sample j ($j=1,\ldots,N$), B_j the total biomass in sample j, L_{ij} the cumulative longevity class i in sample j, T_j the trawling frequency in year^{-1} in sample j, G_j the gravel content corresponding to either low (L), medium-low (M-L), medium (M) or high (H) gravel content in sample j, and ε_{ij} normally distributed errors. Because the longevity composition does not respond linearly to gravel, this covariate was made categorical according to the 25th, 50th and 75th percentile of its distribution, thereby showing a better fit. Trawling frequency was square root-transformed to reduce the influence of a few high outlying values. In order to take into account the dependencies of samples taken from the same spatial location or year, sampling station and year were included as random intercepts and assumed to follow a normal distribution.

The model selection of both random effects and fixed effects were progressed in a forward manner from the initial model, using the R package 'glmmTMB' (Brooks *et al.*, 2017). The initial model was first used to test whether the random effects structure could be extended with a random slope of longevity per station (similar to Pérez Rodríguez and van Kooten (2019)), which allows the slope of the relationship between longevity and the response variable to vary among stations. We also compared models that included year as a fixed effect versus year as a random intercept. After finding the best random effect structure, two-way interactions between the three main covariates (longevity, trawling frequency and gravel) were explored. Next, models were constructed with the remaining hypothesized habitat covariates added, one each time, including orbital and tidal velocity, mean and maximum wind speed, and depth. As a last step, interactions between trawling intensity and orbital velocity, tidal velocity, mean wind speed, maximum wind speed and depth with longevity and trawling intensity were tested, as previous studies found significant interactions between trawling and natural disturbance (Rijnsdorp *et al.*, 2018; Pérez Rodríguez and van Kooten, 2019).

Two criteria were evaluated in model selection: Akaike Information Criterion (AIC) and mean squared error (MSE) from cross-validation. Model selection was initially done following the AIC. However, AIC turned out to be less sensitive to overfitting when models became complex. Several plausible models had similar AIC values, and model fitting seemed to be sensitive to small changes in the input data, suggesting overfitting. Furthermore, the final model was expected to be used for predictions, so predictive performance of the models was in this case considered to be another important aspect of model selection, in addition to model fit (i.e. AIC). Therefore, a cross validation procedure was set up, leaving one sample (with three observations each) out each time. Both models with and without random slope for longevity were included to see how well models with random slope, which generally had the lowest AIC and thus the best fit, were predicting compared to models without random slope. The MSE was calculated and compared between models. This indicated that models with a random slope of longevity had a higher MSE than models without random slope of longevity, suggesting that the random slope models were more prone to overfitting the data and had a higher prediction error. Out of the remaining models with only random intercepts for station and year, the MSE was compared to assess which covariates and interaction of covariates should be included in the final model.

As previously mentioned, the constructed final model was expected to be used to predict the benthic state across the entire spatial extent of the 'Noordzeekustzone'. However, since the random station intercept does not take into account the spatial auto-correlations, it has limited ability in predicting at locations where sampling was not conducted. This means that one has to assume that the variation between stations is zero, despite the indications that including this variation improves model fit. To obtain full spatial predictions, it was decided to construct the final model using INLA (integrated nested Laplace approximation) (Rue *et al.*, 2009), which allows for incorporating a spatial-temporal correlation structure to replace the station and year intercept. In this way, the spatial variation between sampling stations could be included in the model and used later on when predicting the benthic state across the 'Noordzeekustzone'. Furthermore, the variation between years for individual stations could be incorporated as well. Based on the resulting spatial random effects for station, a random effect was estimated for each location on the pre-defined spatial grid used in the benthic state prediction.

Models were also validated by assessing the residuals. Furthermore, it was investigated whether very high cumulative biomasses proportions (i.e. one longevity class dominating the biomass) might influence the results, including those specifically of *Ensis* (razor clam), which is known to occur in very high densities in the Dutch coastal zone (Troost et al., 2021). These additional analyses were done with the final model in glmmTMB and not INLA, as constructing new INLA models for the additional analyses would be disproportionally time consuming. As model parameter coefficients of the final model constructed with glmmTMB or INLA were very similar, this was deemed appropriate.

2.3 Predicting benthic state

A spatial grid was constructed across the 'Noordzeekustzone' with grid cells of 0.0167 degree longitude by 0.0083 degrees latitude. Average surface area was approximately 1 km^2. All calculations of the benthic state were done at the level of the grid cells.

The current and future state of the benthic community was assessed by the Relative Benthic State (RBS), which is developed by (Hiddink *et al.*, 2017; Pitcher *et al.*, 2017; Rijnsdorp *et al.*, 2018; Hiddink *et al.*, 2019; Rijnsdorp *et al.*, 2020). It is based on general, mechanistic assumptions about population dynamics, and therefore also referred to as the 'PD method' (ICES, 2019). The RBS is the biomass of the benthic community (B) as a fraction of the maximum potential biomass of the community when no trawling takes place (K). It is calculated as B/K and varies between 0 and 1. A low RBS indicates that the benthic community is highly impacted by fishing.

The PD method requires information on the depletion rate by the fishing gear, which is calculated from the fraction of benthos that does not survive a trawl passage. It depends on the penetration depth of the gear. It was assumed that a shrimp trawl has a similar depletion as an otter trawl with bobbins, which is estimated to be 0.06 (Hiddink *et al.*, 2017; Rijnsdorp *et al.*, 2020).

The RBS in each grid cell under the two different scenarios was calculated using the parameters of the final longevity composition model as constructed using INLA, habitat information, the trawling frequency as predicted by the spatial fishing effort model (Wilkes *et al*., in prep), the depletion value and the recovery rate of the benthos, which is dependent on longevity (Hiddink *et al.*, 2019).

Analyses were performed in the programme R (R Core Team, 2021), and packages 'glmmTMB' (Brooks *et al.*, 2017) and 'R-INLA' (https://www.r-inla.org/; Rue *et al.*, 2009). Scripts are stored at: https://git.wur.nl/fishing-benthos-impact/VIBEG.

3 Results

3.1 Longevity composition model

The final INLA model indicated that the longevity composition varied with longevity, trawling frequency, depth, orbital velocity and gravel content (Table 3.1). The model suggests that the cumulative proportional biomass with longevity up to 10 years decreases with increasing trawling frequency (Figure 3.1). This cumulative proportional biomass covers the classes <1 yr, <3 and <10 yr, meaning that when their biomass decreases, the biomass of species living >10 yr (which is not included as its cumulative value would be always 1) increases. The model therefore indicates that the proportional biomass of long-lived species (>10 years) increases with increasing trawling frequency. Similarly, a negative relationship was observed between depth and the cumulative proportional biomass with longevity up to 10 years, indicating that the proportional biomass of long-lived species (>10 years) increases with increasing depth (Figure 3.1).

Table 3.1
Parameter mean estimates, standard deviation and 2.5th and 97.5th percentile of the fixed effects of the final longevity composition INLA model.

Variable	Parameter	Estimate	Standard deviation	2.5th percentile	97.5th percentile
β_0	intercept	-1.569	0.433	-2.447	-0.739
L	ln(longevity)	1.949	0.151	1.653	2.245
T	sqrt(trawling)	-0.231	0.083	-1.359	-0.096
D	Depth	-0.060	0.016	-1.363	-0.057
O	Orbital velocity	-0.516	0.943	-1.242	0.156
G_{M-L}	gravel_{M-L}	-0.725	0.321	-0.390	-0.063
G_M	gravel_M	-0.714	0.332	-0.091	-0.028
G_H	gravel_H	-0.548	0.356	-2.365	1.347
L × G_{M-L}	ln(longevity) × gravel_{M-L}	0.865	0.202	0.469	1.261
L × G_M	ln(longevity) × gravel_M	0.687	0.207	0.282	1.093
L × G_H	ln(longevity) × gravel_H	1.214	0.217	0.788	1.640
L × O	ln(longevity) × orbital velocity	-0.935	0.537	-1.991	0.120

A significant interaction effect between longevity and gravel content was found, demonstrating that the effect of longevity on the cumulative proportional biomass depends on gravel content. The longevity composition in areas with a very low gravel content were inhabited by communities with a higher proportional biomass of long-lived (>10 yr) species than in areas with higher gravel content. (Figure 3.1, Figure 3.2). Areas with high gravel content were inhabited by communities with relatively the lowest proportion of long-lived species. Areas with medium gravel content showed a slightly higher proportion of long-lived species than areas with medium-low gravel content. Yet, looking at very short-lived species (<1 year) under no trawling and median conditions of depth and orbital velocity, areas with very low gravel content (black line in Figure 3.2) have a higher proportional biomass of such species than areas with higher gravel content.

Another significant interaction was observed between longevity and orbital velocity. The model demonstrates that the cumulative proportional biomass of long-living species (>10 years) increases with increasing orbital velocity (Figure 3.1).

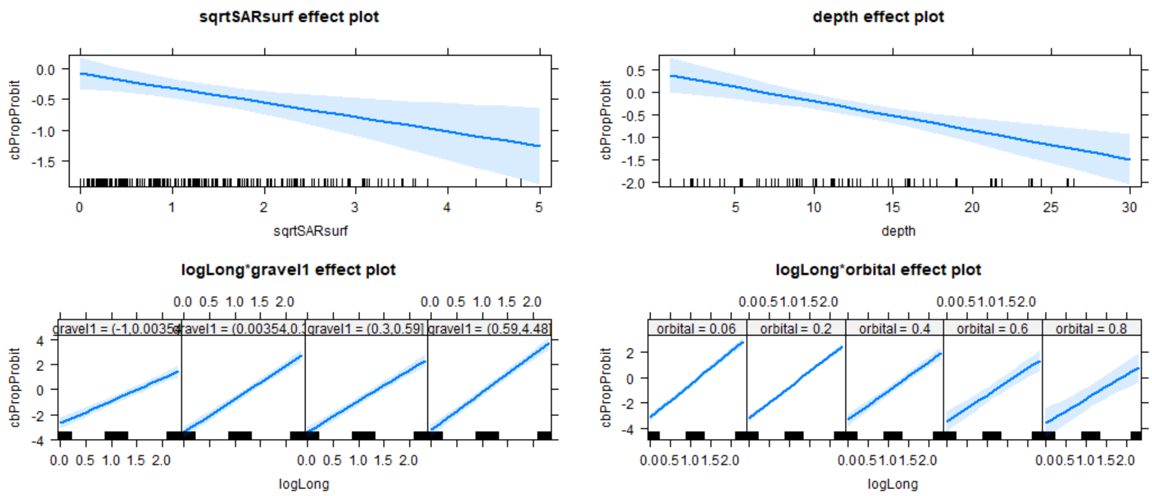

Figure 3.1 *Plotted response of the cumulative proportional biomass (probit-transformed) against SAR, depth, gravel, orbital velocity and longevity. The cumulative proportional biomasses (probit-transformed, on the y-axis of all plots) were included as three longevity classes: <1 year, <3 years and <10 years. Response of the proportional (not-cumulative) biomass of species >10 years with the predictor variables can be inferred indirectly from the plots as follows: a positive response of the cumulative proportional biomass up to 10 yr in the plot indicates a negative response of the proportional biomass of long-lived species (>10 yr) to the predictor variable. Top-left: response to SAR (square root-transformed). Top-right: response to depth (m). Bottom-left: response of the cumulative proportional biomass (y-axis) by longevity (x-axis, log-transformed) and gravel content (four panels, from low to high gravel content). Bottom-right: response of the cumulative proportional biomass (y-axis) to longevity (x-axis, log-transformed) and orbital velocity (five panels, from low to high orbital velocity). Black tick marks at the bottom of each plot indicate observational data that served as input to the model. Note that these plots were produced using the 'effects' R package* (Fox and Weisberg, 2019) *from the final model in glmmTMB, rather than in INLA (the 'effects' package does not support INLA model format), but parameter coefficients are very similar between glmmTMB and INLA.*

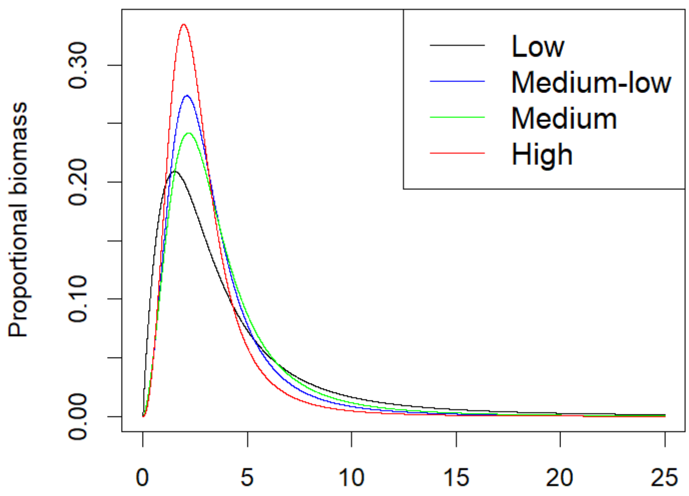

Figure 3.2 *Longevity composition of the untrawled community at the four different levels of gravel content. The median depth (6 m) and orbital velocity (0.15 m/s) in the 'Noordzeekustzone' were selected to produce the longevity composition.*

Model residuals were assessed, and some additional analysis were conducted on the influence of outlying biomass values. Assessment of the model residuals indicated a pattern for observations with either a very low or high proportional cumulative biomass (Figure 3.3). Firstly, running the model with longevity class as a categorical variable did not solve this issue, yet clearly improved model fit. This was indicated by a lower AIC (2663 for longevity as continuous and 2591 for longevity as categorical). However, predicting benthic state requires longevity to be a continuous variable.

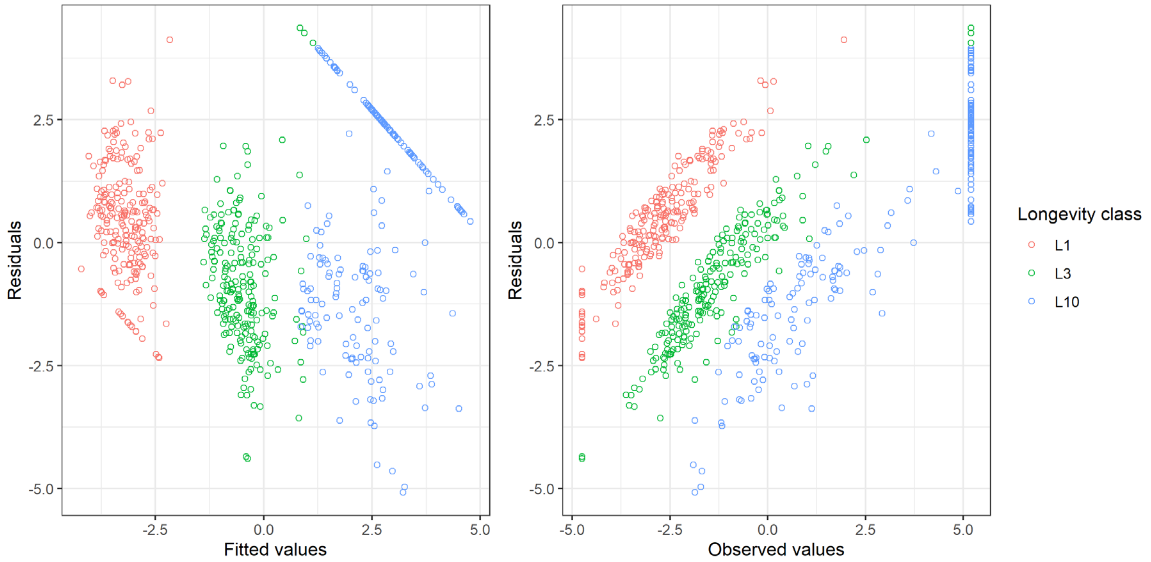

Figure 3.3 *Residuals of the best model (constructed in glmmTMB) against fitted values (left) and observed values (right). Fitted and observed values are probit-transformed. Residuals are coloured by the cumulative proportional longevity class. The pattern of residuals is seen by the diagonal lines of points in the left plot and vertical lines of points in the right plot.*

Secondly, it was assessed whether removing observations (175 out of 669) with very low (<0.00001) or high (>0.9) cumulative proportional biomass of one longevity class would improve the model residuals. This was indeed the case (i.e. no more patterns visible; Figure 3.4), yet the significant effect of depth and the interaction effect between gravel and longevity were not present anymore, suggesting that such removal of observations has a large impact on the results.

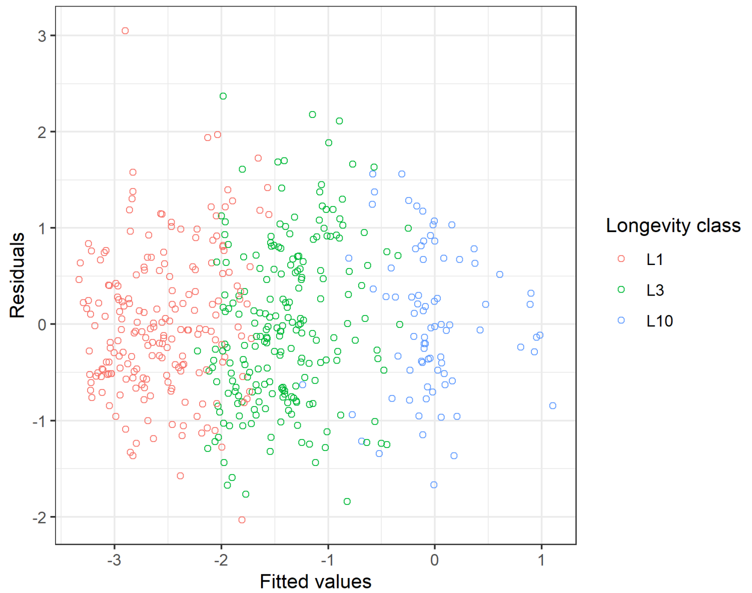

Figure 3.4 *Residuals against fitted values of glmmTMB model where observations of cumulative longevity classes were removed that were either dominating the biomass (proportion >0.9) or that had very low proportions (<0.00001). Fitted values are probit-transformed.*

As *Ensis* was particularly dominating several samples with very high biomasses (relating also to the analysis described above), it was assessed whether adding the proportional biomass of *Ensis* as categorical variable (low/medium/high) to the model as a fixed effect would improve model fit and model residuals. Model fit slightly improved (AIC decreased from 2663 to 2659), yet the patterns in model residuals remained.

3.2 Predicted fishing effort

In the current VIBEG situation, based on the spatial fishing effort model, there was a predicted SAR hotspot of approximately 8 $year^{-1}$ in the 'Noordzeekustzone' between the islands of Vlieland and Terschelling. Because of the assumption that not all fishermen respect the current closed areas, the predicted SAR was above zero in most VIBEG zone-I areas, but zero or close to zero in the most southern (Petten I) and eastern (Rottum I oost) area (Figure 3.5).

In the new situation, the fisheries dynamics model predicted SAR to be zero inside the new VIBEG zone-I areas (Figure 3.5). Because of the fully respected closure of VIBEG areas in the new situation, while maintaining the same total hours fished as in the current situation, a displacement was predicted in fishing intensity from outside the new VIBEG areas and the northeastern part of the 'Noordzeekustzone' to the southwestern part (Figure 3.6). Yet, the hotspot around the closed area Stortemelk in between Vlieland and Terschelling remained.

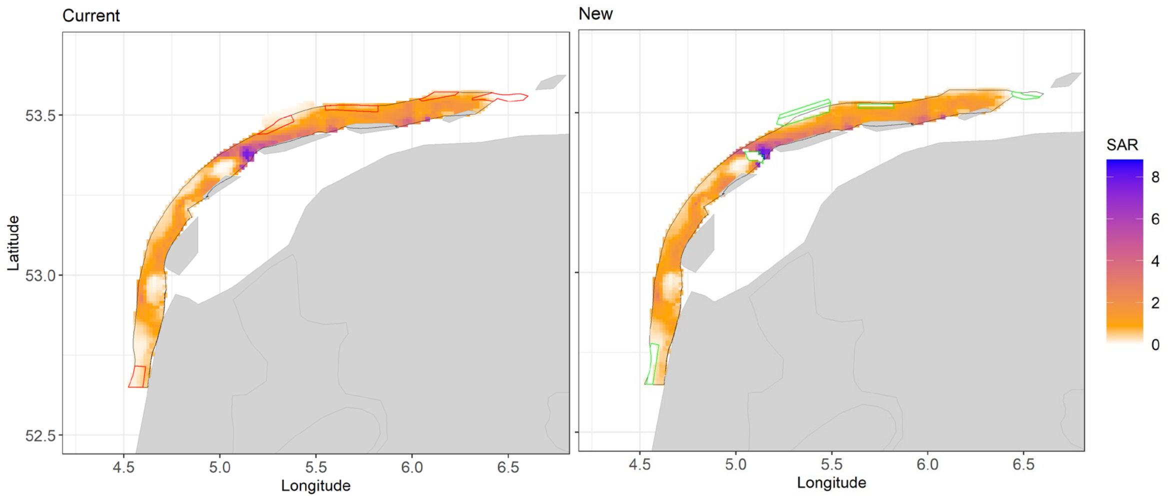

Figure 3.5 *Predicted swept area ratio of the shrimp fleet in the current and new VIBEG situation. Red and green lines indicate the current and new VIBEG zone-I areas respectively. Black line delineates the 'Noordzeekustzone'.*

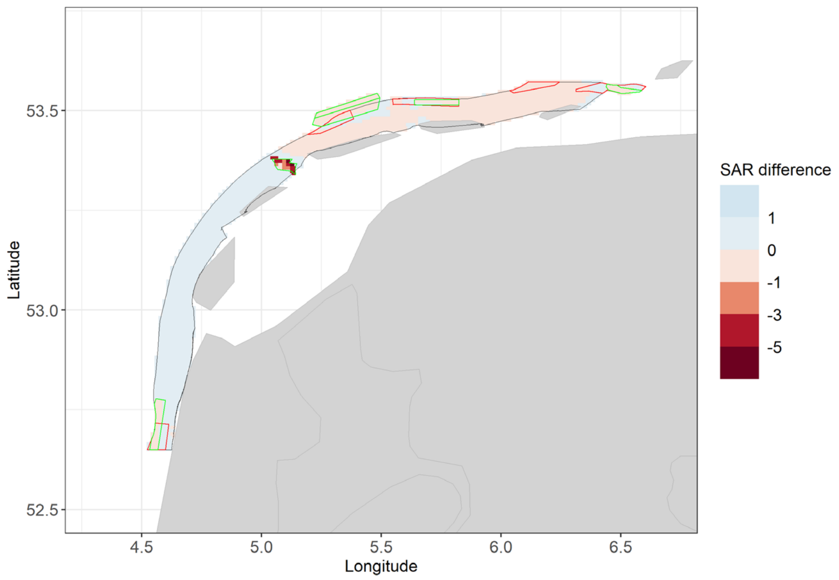

Figure 3.6 *Difference in the predicted swept area ratio between the new and current situation. Positive values (in blue) indicate higher SAR in new situation, negative values (in red) indicate lower SAR in new situation. Red lines: VIBEG areas in current situation, green lines: VIBEG areas in new situation. Black line delineates the 'Noordzeekustzone'.*

3.3 Predicted benthic state

In the current situation, the Relative Benthic State is predicted to be overall highest in the southwestern part of the 'Noordzeekustzone' (Figure 3.7). Areas with high RBS generally coincide with areas with low fishing intensity, and vice versa (Figure 3.5, Figure 3.8). Areas with very low gravel content are predicted to be inhabited by communities with a lower RBS compared to areas with higher gravel contents (Figure 3.8). The area of low RBS (~0.5) north of Terschelling coincides with an area of low gravel content and high orbital velocity.

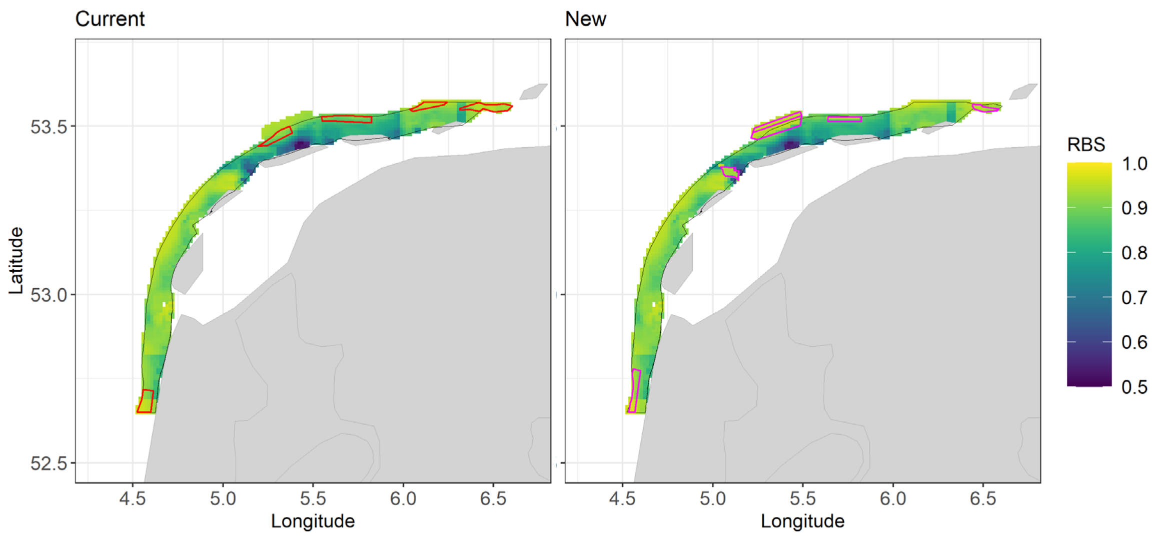

Figure 3.7 *Predicted Relative Benthic State in the current and new VIBEG situation. Red and purple lines indicate the current and new VIBEG zone-I areas respectively. Black line delineates the 'Noordzeekustzone'.*

A higher benthic state is predicted in the new VIBEG zone-I areas compared to current situation (Figure 3.7, Figure 3.9). Yet, differences in RBS between the new and current situation are small, with the exception of the closed area Stortemelk in which the RBS increases in some grid cells with more than 0.2. Overall, the RBS slightly decreases (i.e. worsens) in the south-eastern region and slightly increases (i.e. improves) in the north-western region of the 'Noordzeekustzone' (Figure 3.9).

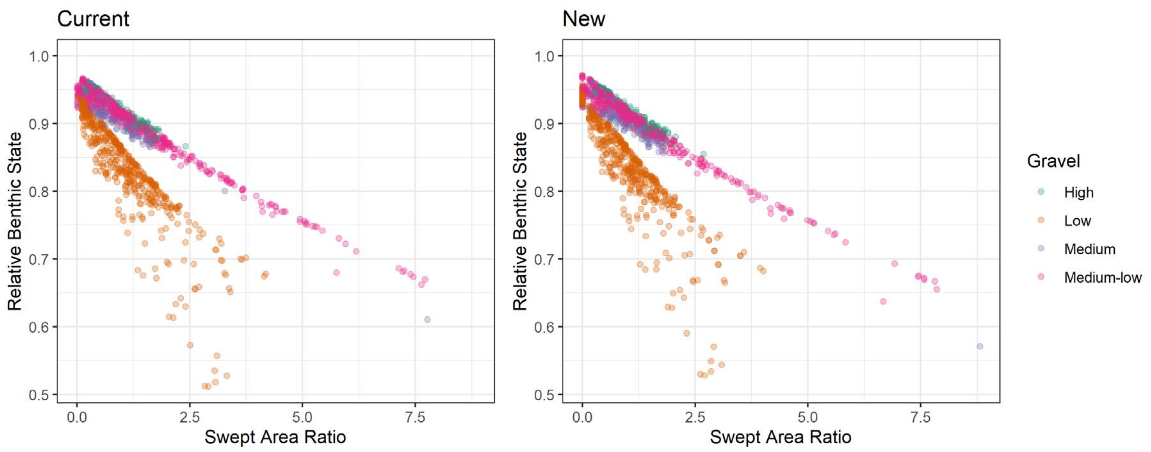

Figure 3.8 *Predicted Relative Benthic State in the current and new VIBEG situation against the predicted Swept Area Ratio in the 'Noordzeekustzone'. Colours indicate gravel content.*

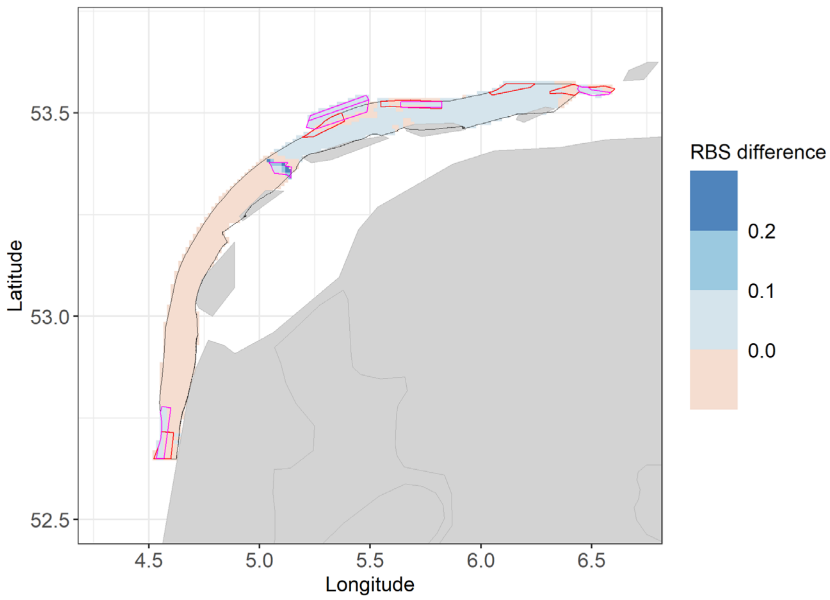

Figure 3.9 *Difference in the predicted Relative Benthic State between the new and current situation. Positive values (in blue) indicate higher RBS in new situation, negative values (in red) indicate lower RBS in new situation. Red lines: VIBEG areas in current situation, purple lines: VIBEG areas in new situation. Black line delineates the 'Noordzeekustzone'.*

The overall distribution and range of the predictive RBS between the current and new situation are similar (Figure 3.10). Yet, the new situation leads to a slightly higher RBS compared to the current situation (Table 3.2).

Table 3.2
Mean and median predicted Relative Benthic State for the current and new VIBEG situation.

RBS	Current	New
Mean	0.882	0.884
Median	0.900	0.902

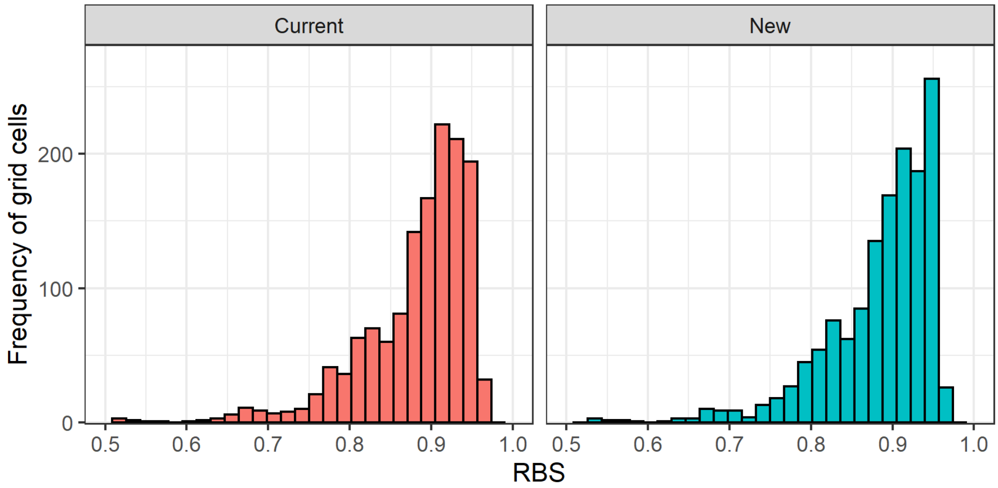

Figure 3.10 *Histogram of the predicted Relative Benthic State in the current and new situation.*

4 Discussion & conclusion

In this report, a statistical model was developed for the longevity composition of benthic communities in the Dutch coastal zone. The model was used to predict the Relative Benthic State for two situations in the 'Noordzeekustzone', varying in the location of areas closed to fishing and therefore in a different simulated distribution of fishing effort. The methodology used here has been developed into a European-wide regional assessment framework by the working group on Fisheries Benthic Impact and Trade-offs of the International Council for the Exploration of the Sea (ICES), in light of the Marine Strategy Framework Directive (ICES, 2019). The North Sea regional assessment makes use of the statistical model developed for offshore areas in the North Sea by Rijnsdorp et al. (2018). It also predicts into the Dutch coastal zone. However, the Rijnsdorp et al. model is not based on data from benthic communities and habitat variables in the coastal zone. The statistical model developed here is based on such data and is therefore more suitable to be applied to coastal areas. Although this study only included data from shrimp trawl fisheries, this fishery is the dominant trawling activity in the Dutch coastal zone. Yet, trawling activity of other countries has not been included.

The statistical model indicated that the longevity composition of benthic communities in the Dutch coastal zone varies between areas with different gravel contents. A similar relationship was found by Rijnsdorp et al. (2018) for offshore benthic communities in the North Sea. Yet, the range in gravel content was very large in that study, varying from 0-92% compared to 0-4% in the current study. The relationships found in these two studies are therefore not directly comparable. Offshore communities in gravel-dominating areas (>50%) displayed according to Rijnsdorp et al. a higher proportion of long-lived species (>10 years) than in less gravelly areas, whereas offshore communities in areas with very low gravel content displayed a low proportional biomass of long-lived species. This study on communities in the coastal zone focused on variations in gravel content within areas of low gravel content and identified the relationship between longevity and gravel content for those communities and habitats specifically.

We observed a positive relationship between trawling intensity and the proportional biomass of long-lived species (>10 years). This is against the expectation that long-lived species are most sensitive to trawling due to their slow recovery after disturbance. The model also indicated that the proportional biomass of long-lived species increases with increasing orbital velocity – a proxy for natural disturbance. Yet, both Rijnsdorp et al. (2018) and Pérez Rodríguez & Van Kooten (2019) observed similar relationships for areas under high natural disturbance in offshore communities and in the coastal communities of the 'Noordzeekustzone', respectively. Pérez Rodríguez & Van Kooten hypothesized that under extreme disturbance – whether from a natural or anthropogenic source – the best survival strategy is perhaps not to be short-lived and have a fast recovery, but to have a reduced vulnerability by being hard (e.g. a thick shell) and large, as many long-lived species are. An example from the Dutch coastal zone is the relatively abundant common heart urchin (*Echinocardium cordatum*). Another important trait that relates to vulnerability is burrowing: deep-burrowing species such as the common heart urchin may not be impacted by the shrimp trawl gear, as the gear penetrates the sediment with only a few centimetres. Rijnsdorp et al. (2018) did not observe an effect of trawling on the longevity composition of offshore communities when focussing on deep-burrowing (>5 cm) taxa only. Another taxon that is not very vulnerable to trawling is *Ensis*, as observed by Tulp et al. (2020) in response to shrimp fisheries in the Dutch Wadden Sea. Although *Ensis leei* (the most common species of the genus found in the Dutch coastal zone) is not highly long-lived (3-10 years), it is large, has a shell and can burrow itself deeply and very quickly, and can even jump or swim away in response to disturbance. Therefore, these studies, including ours, suggest that longevity alone is not enough to fully capture and understand the response of benthic communities to trawling.

Our model identified a negative relationship between the cumulative proportional biomass of species with longevity <10 year and depth, indicating that the proportional biomass of long-lived species (>10 years) is lowest in shallow waters and highest in deeper waters (up to 40 m in the 'Noordzeekustzone').

Depth may serve as a proxy for natural disturbance, with shallow waters being likely more prone to the impact of tides and waves. However, our model suggests that depth has the opposite of the effect that orbital velocity has on the longevity composition. Therefore, depth likely reflects in this model other habitat variables (e.g. light, food conditions) that may influence the longevity composition.

The statistical model constructed here differs from the type of model developed by Rijnsdorp et al. (2018) and used by the WGFBIT. Instead of assuming that the cumulative biomass proportions are integers and follow a binomial distribution, requiring a Generalized Linear Mixed Model (GLMM), we used a probit-transformation on the cumulative biomass proportions and thereby assumed they follow a normal distribution. This allowed us to use the more simple Linear Mixed Model approach, thereby avoiding model convergence issues and low variance of random effects encountered with the GLMM approach (Rijnsdorp *et al.*, 2018; Van Denderen *et al.*, 2020). Yet, our models displayed some unusual residual patterns for observed values with either very low or high cumulative biomass proportions that require further investigation.

As also referred to by Rijnsdorp et al. (2018), the North Sea has a long history of fishing, including bottom trawling. Therefore, the benthos communities sampled here may already represent communities that are highly impacted by fishing, and any highly vulnerable species may already have disappeared. It could therefore be that the fishing impact studied here is an underestimation of what the impact would be on a benthic community in a more pristine state.

The predicted distribution of fishing effort in the new VIBEG situation led to a minor improvement of the overall Relative Benthic State in the 'Noordzeekustzone' compared to the current situation. The RBS slightly improved in the north-eastern part and a slightly declined in the southwestern part. The closed VIBEG area 'Stortemelk' in the new situation overlaps with an area of high simulated fishing effort. Closing this area therefore is predicted to result in a strong increase in RBS there. As communities in areas with low gravel content tended to have a lower proportional biomass of long-lived species (>10 years) than those with a higher gravel content, areas with naturally low gravel content are predicted to have a lower RBS in general. Similarly, areas with high orbital velocity are also predicted to have a lower RBS than areas with lower orbital velocities. In deeper waters in the coastal zone, however, the model predicts that these are inhabited by communities with a relatively high proportion of long-lived species, thus a higher RBS, than in shallow waters.

We have developed a statistical model for the relationship of the longevity composition of benthic communities with trawling frequency of shrimp fisheries and habitat conditions for the Dutch coastal zone specifically. A key finding was that benthic communities in a highly fished or disturbed areas seem to be inhabited by species that are relatively long-lived, which is against the general expectation that long-lived species are most vulnerable to trawling due to their slow recovery after a disturbance.

The RBS method used to calculate trawling impact also assumes that trawling favours short-lived species, as it is built on the assumption that organisms with a short lifespan recover faster after trawling. The contrast between this assumption and our findings leads to the question if the RBS method is applicable or not for a system where we find higher longevity at more intensively trawled sites.

To answer this question, we need to consider the potential underlying mechanisms of the observed pattern. Increased longevity with trawling can occur because long-lived individuals are well-protected against trawling, for example because they can bury deeply into the sediment, where they are safe from the gear. Trawling would lead to a relative increase of such species. Furthermore, such resistant species could benefit indirectly from trawling, because they could have a competitive advantage over more vulnerable species, and hence their absolute abundance could also increase with trawling intensity. The RDS approach gives up much of the ecological complexity of natural systems in favour of a general conceptually sound framework. Neither of the potential causes of the positive relationship between trawling and longevity we found are considered in the RDS approach. Yet, this does not invalidate the RDS as a good indicator of benthic impact of bottom trawling. It does however mean that we cannot interpret the RDS as the ultimate biomass abundance under the prevailing trawling regime, and that we must restrict our interpretation to a somewhat more abstract effect of bottom trawling on the benthos community.

The application to the current and newly proposed VIBEG areas shows that scenarios with identical fishing effort can be tested using the current tool, to find the best option for the benthic community.

5 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2021. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

Furthermore, the chemical laboratory at IJmuiden has EN-ISO/IEC 17025:2017 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2021 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation. The chemical laboratory at IJmuiden has thus demonstrated its ability to provide valid results according a technically competent manner and to work according to the ISO 17025 standard. The scope (L097) of de accredited analytical methods can be found at the website of the Council for Accreditation (www.rva.nl).

On the basis of this accreditation, the quality characteristic Q is awarded to the results of those components which are incorporated in the scope, provided they comply with all quality requirements. The quality characteristic Q is stated in the tables with the results. If, the quality characteristic Q is not mentioned, the reason why is explained.

The quality of the test methods is ensured in various ways. The accuracy of the analysis is regularly assessed by participation in inter-laboratory performance studies including those organized by QUASIMEME. If no inter-laboratory study is available, a second-level control is performed. In addition, a first-level control is performed for each series of measurements.
In addition to the line controls the following general quality controls are carried out:

- Blank research.
- Recovery.
- Internal standard
- Injection standard.
- Sensitivity.

The above controls are described in Wageningen Marine Research working instruction ISW 2.10.2.105. If desired, information regarding the performance characteristics of the analytical methods is available at the chemical laboratory at IJmuiden.

If the quality cannot be guaranteed, appropriate measures are taken.

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Justification

Report C038/22
Project Number: 4318100322

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: S.T. Glorius Msc. BSc.
Colleague Scientist

Signature: 

Date: 14 July 2022

Approved: Drs. J. Asjes
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