Gas extraction under intertidal mudflats is associated with changes in sediment structure and macrozoobenthic invertebrate communities

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Abstract

1- Gas withdrawal from subterranean layers may generate land subsidence with consequences for soil micro-structure, hydrology, and ultimately local biological communities. In intertidal environments, land subsidence may change the local flooding regime and sediment composition, two main drivers of the macrozoobenthic community structure. In the Dutch Wadden Sea, a UNESCO world heritage site, gas extraction has resulted in an average subsidence of up to 2 mm y^{-1}, of sand dunes, salt marshes and intertidal mudflats. These mudflats support a highly productive macrozoobenthic community, which offers important feeding grounds for birds and fishes. To what extent land subsidence due to gas extraction affects the macrozoobenthos remains unknown and increasingly important given sea level rise.

2- Taking advantage of an extensive monitoring program of the macrozoobenthic community, we evaluated the effect of anthropogenically caused land subsidence on sediment composition and intertidal macrozoobenthos. Nearly 4600 points were sampled yearly (2008-2020) across the Dutch Wadden Sea, allowing us to compare sediment composition and macrozoobenthos biomass within and outside the subsidence area while controlling for the main drivers of these variables. With an

INLA-spde approach we could account for spatial and temporal autocorrelation. We also compared population trends within and outside subsidence area for 31 species with different habitat use in terms of depth and sediment composition.

3- We found that median grain size of the sediment has decreased in the subsided area at 1 µm y^{-1} while on average remaining constant in the rest of the intertidal mudflats. Mud fraction was 3% higher within the subsided area throughout the studied period. This had no effect on the total biomass of macrozoobenthos. However, the biomass of species that prefer deeper areas increased within the subsidence area compared to the area outside the subsidence area, and the opposite was true for species that prefer shallower places.

4- Policy implications: studies suggest that the present subsidence will not result in the drowning of the mudflat. However, we show that changes in sediment- and macrozoobenthic community composition might be happening. We call for definitions and thresholds of effects for a better management of the Wadden Sea

Keywords: anthropogenic impact, inla, land subsidence, sediment composition, soft bottoms, spde, wadden sea

Introduction

The extraction of underground oil or gas modifies the structure of subterranean layers and can lead to land subsidence with consequences for the environment at different scales (Milliman & Haq 1996, Ko & Day 2004). As a consequence, habitat availability for plants and animals is also affected, and local ecosystems are transformed (e.g. Li et al. 2019, Turner & Mo 2021). When land subsidence occurs in intertidal areas -regions that are submerged during high tide and emerge during low tide- it alters the local flooding regime. If subsidence rates are low relative to the sediment supply by water, subsidence can be partially or completely compensated by sedimentation (Wang et al. 2018). At high subsidence rates, however, intertidal areas may almost permanently inundate. This could be aggravated by increased erosion, as deeper areas permit stronger waves and shear stress (Wang et al. 2018). Both sedimentation and erosion, together with sediment

supply, will ultimately determine the sediment composition of a particular area in a mudflat. Because subsidence changes depth, which partially determines sedimentation and erosion regimes, subsidence may ultimately change local sediment composition. Nevertheless, sediment composition can also be affected by other factors such as anthropic activities and ecosystem engineers (Eriksson et al. 2010, Donadi et al. 2015b).

The flooding regime and the sediment composition of the seafloor are key drivers of intertidal macrozoobenthos (Van Colen 2018) -invertebrates larger than 1 mm that live in close association with the substrate. Areas more frequently inundated will experience different environmental conditions (Beukema 1976), different predation pressure (e.g. Sanchez-Salazar et al. 1987) and may have different access to food (e.g. filter feeders). Sediment size composition determines the amount of organic matter in the seafloor (e.g. Yang et al. 2021), which determines the stability of the seafloor (Bartzke et al. 2013; but see Defew et al. 2002), and in turn the amount of food for macroinvertebrates (Christianen et al. 2017), as well as their behaviour (e.g. Wiesebron et al. 2021).

The Wadden Sea, the largest cohesive intertidal area in the world and a UNESCO world heritage site, is subject to gas extraction, which has resulted in land subsidence (Fokker et al. 2018). Macroinvertebrates of the Wadden Sea are an important part of the food web as a feeding resource for birds (e.g. Beukema & Dekker 2019) and fishes (Poiesz et al. 2020). Because sediment composition and flooding regime, two of the key factors that determine the occurrence and abundance of macrozoobenthic species, could be affected by land subsidence, cascading changes to the macrozoobenthic community are likely.

Gas extraction in the Dutch Wadden Sea is managed following the “hand on the tap” principle (NAM B.V 2007), meaning that if an effect on the ecosystem is detected, the gas extraction should be halted. Because of this, subsidence and its consequences are closely monitored. Deep subsidence occurs at a rate of ~2 mm y^{-1} (NAM B.V 2021). However, changes in average seafloor elevation have not been detected yet (van der Vegt 2022) as subsidence has been so far compensated by increased sedimentation (Wang et al. 2018). So far, studies about the impact of gas extraction on mudflats have mostly focused on the risk of intertidal area

loss (e.g. Thienen-Visser et al. 2015, Wang et al. 2018, Fokker et al. 2018, van der Vegt 2022) but changes in sediment and community composition have received less attention (but see Beukema 2002).

To detect and measure human impacts on ecosystems, such as those of land subsidence, is one of the big challenges in applied ecology. Ideally, such effects are examined using a before- after control-impact assessment (BACI, Green 1979). The approach has been successfully employed in many impact assessment studies (e.g. Sansom et al. 2016, Smokorowski & Randall 2017), there are shortcomings (e.g. Underwood 1991, Smokorowski & Randall 2017). First, the selection of the location and number of control sites can be arbitrary. Second, the observed variability between sites may be the result of spatially varying environmental variables, which confounds our ability to attribute observed changes to the anthropogenic impacts of interest (Hewitt et al. 2001). Last, the need for an impact assessment study is only acknowledged when human activities are already ongoing, and therefore it is impossible to register the unaffected “before” conditions. Large-scale monitoring systems, when properly designed (Field et al. 2007), could overcome some of these shortcomings: all sampling locations could act as control sites, and by also accounting for the effect of all other environmental covariates on the variable of interest, the problem of confounding can be heavily reduced (discussed by Underwood 1993). This means we can detect differences between impact and control sites while accounting for differences in environmental conditions between sites.

The purpose of this study was to investigate potential effects of land subsidence caused by gas extraction on mudflat’s sediment composition and macrozoobenthic communities. To achieve this, we took advantage of thirteen years (2008-2020) of spatially comprehensive monitoring data of sediment composition and benthic intertidal macroinvertebrates. The spatial and temporal extent of these data allowed us to use it as an alternative to a BACI design, and to quantify the effect of local physical and biological conditions on sediment composition (median grain size and mud fraction) and macroinvertebrates biomass. In this way, we can detect differences between ‘within’ and ‘outside’ the subsidence area “over and above” (i.e. while controlling for) these environmental variables. To control for spatiotemporal autocorrelation that cause pseudo replication, a spatial-temporal latent field was also included using the INLA-SPDE approach (Lindgren

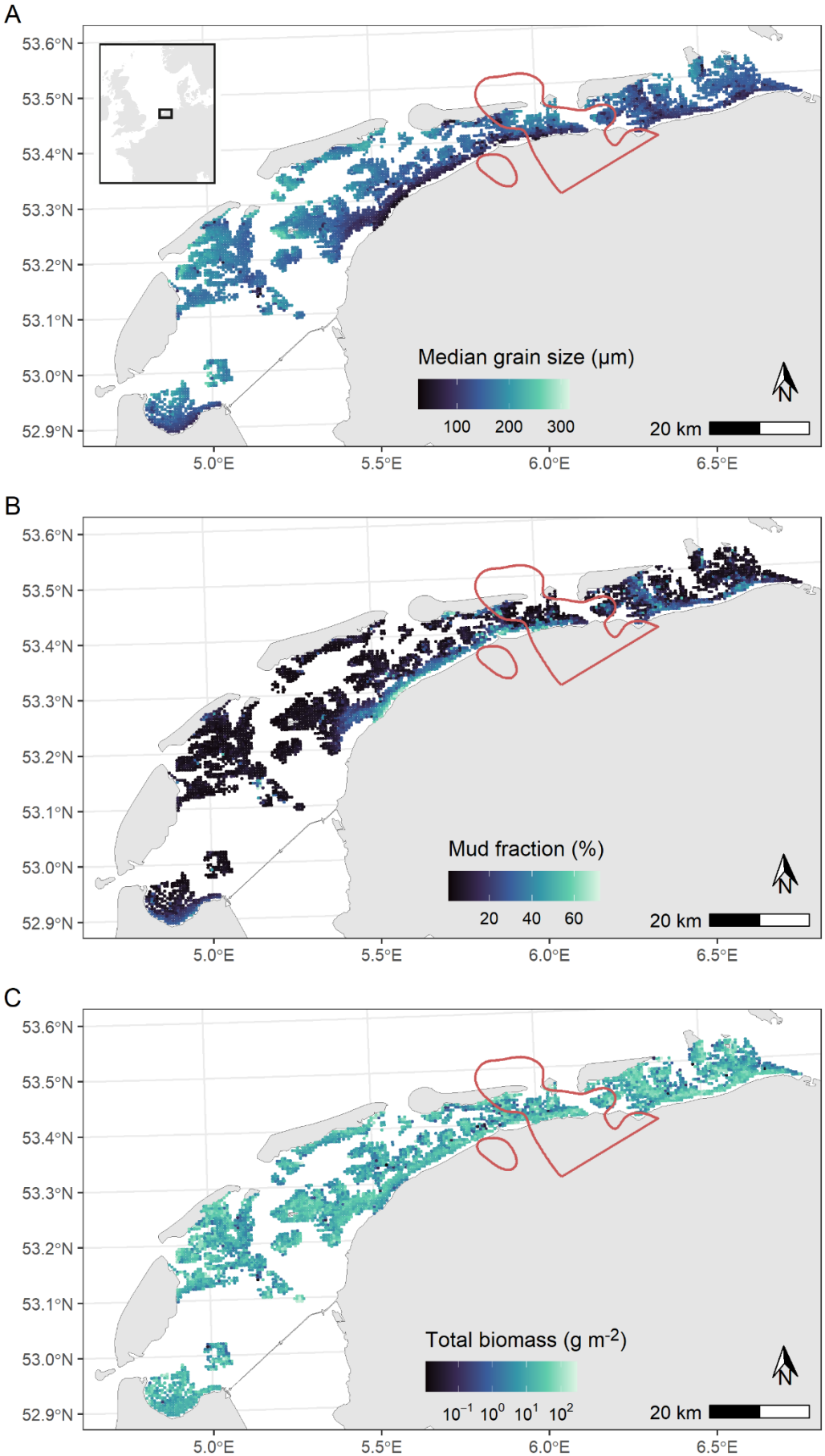
et al. 2011). Because land subsidence will change the local sedimentation regime, first, we asked whether sediment composition was different within compared to outside the area affected by land subsidence due to gas extraction. Second, as depth and sediment composition are two of the main drivers of the benthic community, we then asked whether the abundance of macrozoobenthos was also different within compared to outside the area affected by land subsidence. As total biomass encompasses many different species that favour different abiotic conditions, biomass might increase or decrease in the subsidence area. To clarify how particular species distributions changed, we analysed trends in the ratio of different species' biomass within and outside the subsidence area. We related this ratio to the species' favoured abiotic condition to identify species that may be benefitted or hindered by land subsidence.

Materials and Methods

Study area

The Wadden Sea extends for 8000 km^2 from the north of the Netherlands to the east of Denmark (53° N Lat, Fig 1). It has a bidaily mesotidal regime with a range of 1.4 to 3.4 m across the system (Postma 1982). The soil is composed by sand and mud (Oost 1995). Its macrozoobenthic community is dominated by bivalves and polychaetes, with *Cerastoderma edule, Mya arenaria* and *Arenicola marina* being the most abundant species it terms of biomass (Compton et al. 2013).

Gas extraction started in the area of Ameland in 1986 (Fokker et al. 2018). Since then, measurements of land subsidence have been taken by the Dutch Petroleum Company (NAM, for its acronym in Dutch) through various methods: leveling, every 4 years since 1986, surveying with GPS, once a year since 2006, and Insar measurements (on land only) once a year since 1997 (NAM B.V 2021). These measures were modeled by NAM to determine the contours of deep land subsidence. For this study we use the contours of 1 cm of deep subsidence registered since 2006 (Fig. 1) (NAM B.V 2021).


A
53.6°N
53.5°N
53.4°N
53.3°N
53.2°N
53.1°N
53.0°N
52.9°N
5.0°E
5.5°E
6.0°E
6.5°E
Median grain size (µm)
100 200 300
20 km
N
B
Mud fraction (%)
20 40 60
20 km
N
C
Total biomass (g m-2)
10−1 100 101 102
20 km
N

121

Fig 1: SIBES sampling stations and subsidence contour in red (1 cm of subsidence between 2006 and 2020). **A)** Average (2008-2021) median grain size, **B)** average mud fraction, and **C)** average total macroinvertebrate biomass (measured as ash-free dry mass) at each sampling station.

Survey

Between 2008 and 2020 the macrozoobenthic community and sediment composition of the Wadden Sea were sampled for the synoptic intertidal benthic survey (SIBES). Yearly, the survey consisted of 1441 to 4209 stations of which 54 – 91 % were located on a regular (500 m) grid design and the rest were randomly distributed along the grid (Bijleveld et al. 2012). Of the total of 4580 sampling stations 528 were within the contour of subsidence. Every year, between June and October, each station was visited, and a sample of sediment and the benthic community were taken (for methods see Compton et al. 2013). All animals were fixed in formalin (4% solution) except for bivalves larger than ~1 cm that were frozen. In the lab, individuals were identified to the finest taxonomic level possible, and ash free dry mass (afdm) was measured to 0.1 mg. For a more complete description of the methods see Compton et al. (2013).

Sediment samples were taken with a 33 mm diameter core to a depth of 4 cm and conserved at -20° C. In the laboratory, samples were freeze-dried for 96 h, homogenized with mortar and pestle, weighted and put in 13 ml auto-sampler tubes with degassed reverse osmosis water. Samples were not treated to remove calcium or organic material. Sediment size composition was characterized using a particle size analyzer (Coulter LS 13 320) that measures grain sizes between 0.04 and 2000 µm in 126 size classes through laser diffraction and polarization intensity differential scattering technology. For each sample, the median grain size (mgs) and mud fraction (volume percentage of particles smaller than 63 µm) were obtained.

Covariates

We identified a multitude of environmental variables known to be of importance for the distribution of sediment and macroinvertebrates (Table 1). Depth, current shear stress, wave forcing all determine the amount of energy in a particular place and therefore are associated with sediment composition. Depth is

also an important driver of macroinvertebrates distribution (Kraan et al. 2010, e.g. de Jong et al. 2015). Strong shear stress and waves may dislodge benthic invertebrates, so we also expect these variables to affect their total biomass (e.g. Anta et al. 2013, Malakauskas et al. 2013, but see Donadi et al. 2015a).

In soft sediment systems, seafloor topographic features are correlated with different sediment composition (Trentesaux et al. 1994, e.g. Mestdagh et al. 2020). Different benthic communities are also associated with different topographic features (e.g. Jansen et al. 2018, Mestdagh et al. 2020). For this reason, we included slope, topographic position index (TPI) and topographic ruggedness as covariates to the models for mgs, mud content and biomass.

Sediment composition determines the benthic community (Kraan et al. 2010, e.g. de Jong et al. 2015), therefore, mgs, mud fraction and the standard deviation of sediment size were included in the biomass model. Day of the year was also included in the biomass model to account for periods dominated by growth or mortality.

Large fresh water discharges through the Afsluitdijk, at the southwestern part of the Wadden Sea, produce density stratification, which in turn has an important effect on sediment transport (Elias 2006). Salinity is also an important predictor of habitat type (Baptist et al. 2019) so it was also included in the biomass model.

The lugworm, *Arenicola marina*, the blue mussel *Mytilus edulis* and the Pacific oyster *Crassostrea gigas* are important ecosystem engineers in the Wadden Sea (Volkenborn et al. 2007, Donadi et al. 2015b). *A. marina* removes the sediment resuspending the smaller particles. Oysters and mussels, when filter-feeding, catch the smaller particles suspended in the water column and fix them in the sediment when excreting. The biomass of *A. marina* and the presence of a *M. edulis-C. gigas* bank were used as covariates in the mgs and mud fraction models. *A. marina* biomass was determined through SIBES samples as described in the 'survey' section. Mussel and oyster banks in the Wadden Sea are mapped every year (Troost et al. 2022). Because the effects of such bivalve banks on sediment extent beyond the bank itself (Kröncke 1996), we used the position of bivalve banks plus a buffer of 300 m as indication of bivalve bank presence.

Spatial modelling

We modeled three response variables: sediment mgs (µm), mud fraction (%) and total macroinvertebrate biomass (afdm, g m^{-2}), each using an appropriate error distribution. We used a Gaussian distribution for mgs and a beta distribution with a logit link function for mud fraction (Douma & Weedon 2019). As all the samples contained detectable biomass, a Gamma distribution with a log link was used for total biomass (Zuur et al. 2019).

Covariates described in the previous section and Table 1 were included in the models as fixed-effects. Collinearity between variables was assessed by computing variance inflation factors (VIF) with function 'vif' of car R package (Fox et al. 2011). We sequentially dropped the covariates with the highest VIF until all presented VIF < 2 (Zuur et al. 2010). In this way, topographic ruggedness was dropped from the models. To avoid numerical estimation problems, all covariates were standardized by subtracting their mean and dividing by their standard deviation. We used smoothers when Pearson's residuals from generalized linear mixed models showed patterns relative to covariates.

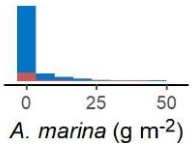
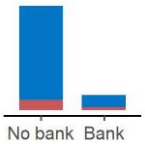
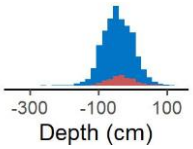
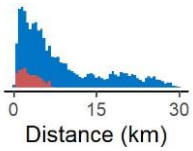
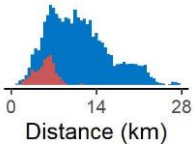
Subsidence was included in the model as a dichotomous variable: each observation was classified as within or outside the subsidence area. We did this because 38% of our observations within the subsidence area fell inside the 1 cm contour, and therefore we did not have enough information to analyze its effect as continuous. We assessed whether the effect subsidence changed in time by adding an interaction term with 'year'. Priors for all fixed effects were set to a mean of zero and a precision of 1. This high prior weight around zero results in the need of more data support for the posterior of a parameter to be different from zero, which makes our results more conservative.

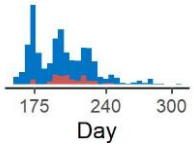
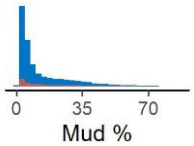
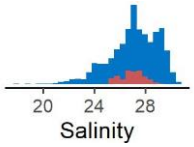
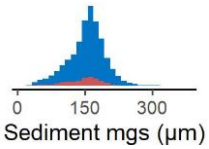
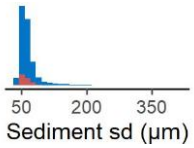
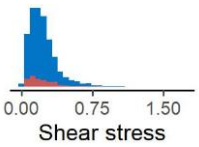
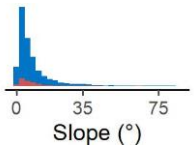
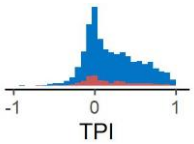
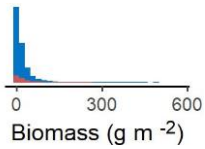
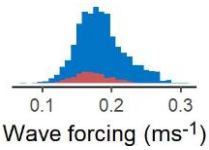
To account for spatial autocorrelation between observations that cannot be explained by the available covariates, a stochastic partial differential equation (SPDE, Lindgren et al. 2011) model was used. In this

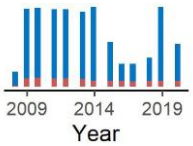
approach, a mesh of triangles is constructed for the study area and used to estimate the spatially- and temporally-structured random component (SPDE specifications in ESM1).

Our main objective with this study was to test if subsidence affected each of the response variables or not, therefore we focused on hypothesis testing rather than on model selection (Fieberg 2022). We considered that subsidence had an effect on sediment or biomass if the confidence interval for its parameter or for the interaction term was different from zero.

Table 1: Alphabetically ordered variables that were included in the models fitted to sediment median grain size (sediment mgs), mud fraction, and total biomass data. Source of the data, year of measurements, and frequency distributions of the data. The colors in the frequency plots indicate outside (blue) and inside (red) the subsidence area.

Variable name	Model used	Source	Years measured	Histogram
Arenicola marina biomass	Sediment mgs Mud fraction	This study	2008-2020	
Bivalve bank presence	Sediment mgs Mud fraction	https://shiny.wur.nl/Schelpdiermonitor_Banken/	2008-2020	
Depth	Sediment mgs Mud fraction Total biomass	Rijkswaterstaat	2005, 2013, 2017	
Distance to coast	Sediment mgs Mud fraction Total biomass	This study	-	
Distance to tidal inlets	Sediment mgs Mud fraction Total biomass	This study	-	

Day of the year	Total biomass	-	-	
Mud fraction	-	This study	2008-2020	
Salinity	Sediment mgs Mud fraction Total biomass	Duran-Matute et al 2014	2013	
Sediment mgs	Total biomass	This study	2008-2020	
Sediment size's standard deviation	Total biomass	This study	2008-2020	
Current shear stress	Sediment mgs Mud fraction Total biomass	Folmer et al. 2016	2009-2010	
Slope	Sediment mgs Mud fraction Total biomass	Derived from "Depth"	2005, 2013, 2017	
Topographic position index	Sediment mgs Mud fraction Total biomass	Derived from "Depth"	2005, 2013, 2017	
Total biomass	-	This study	2008-2020	
Wave forcing	Sediment mgs Mud fraction Total biomass	Donker et al. 2015	2010	

Year	Sediment mgs Mud fraction Total species biomass	-	-	

Species-specific effects of land subsidence

Overall biomass is an aggregate of different species which might be differently affected by subsidence. To analyze if particular species are driving the observed biomass patterns, we identified the more abundant species (in terms of biomass) within the subsidence area, and plotted their relative contribution to total biomass within and outside the subsidence area.

To understand how species with different habitat use are affected by subsidence, we compared population trends within and outside the subsidence area for a larger group of species (ESM2). To classify species' habitat use, for each species, we extracted the median of the 'median grain size' and the median of the depth range in which they occurred. Hereafter we call these median values 'sediment use' and 'depth use'.

To detect differences between population trends, we calculated the ratio between the average biomass within and outside the subsidence area for each species and year. We used a linear mixed model with log('biomass ratio') as response variable, 'depth use' and 'year' as continuous fixed effects, and 'species' as random slope and random intercept. We did not include 'sediment use' in the model to avoid collinearity with 'depth use' (Pearson's correlation: -0.72, $P < 0.001$). We applied a likelihood ratio test to select the best random structure and AIC together with 95% parameter confidence interval to select the best model relative to fixed effects (Zuur 2009).

Results

Median grain size

The average mgs of all samples was 154 ± 41 µm (mean ± sd). The mixed-effects model fitted to mgs revealed a positive effect of distance to coast, current shear stress, topographic position index, wave forcing and salinity, and a negative effect of the presence of bivalve banks and distance to tidal inlet (Fig 2A). The local depth and biomass of *Arenicola marina* had non-linear effects on mgs (Fig 2A). The model revealed an interaction between subsidence and year on sediment size (Fig 2A). This meant that while there was no evidence for a positive or negative trend in sediment median grain throughout the Wadden Sea, within the subsidence area, mgs has been decreasing (Fig 2B). At the end of the study period, the model estimated that mgs within the subsidence area was on average 16 µm smaller than outside (Fig 2B).

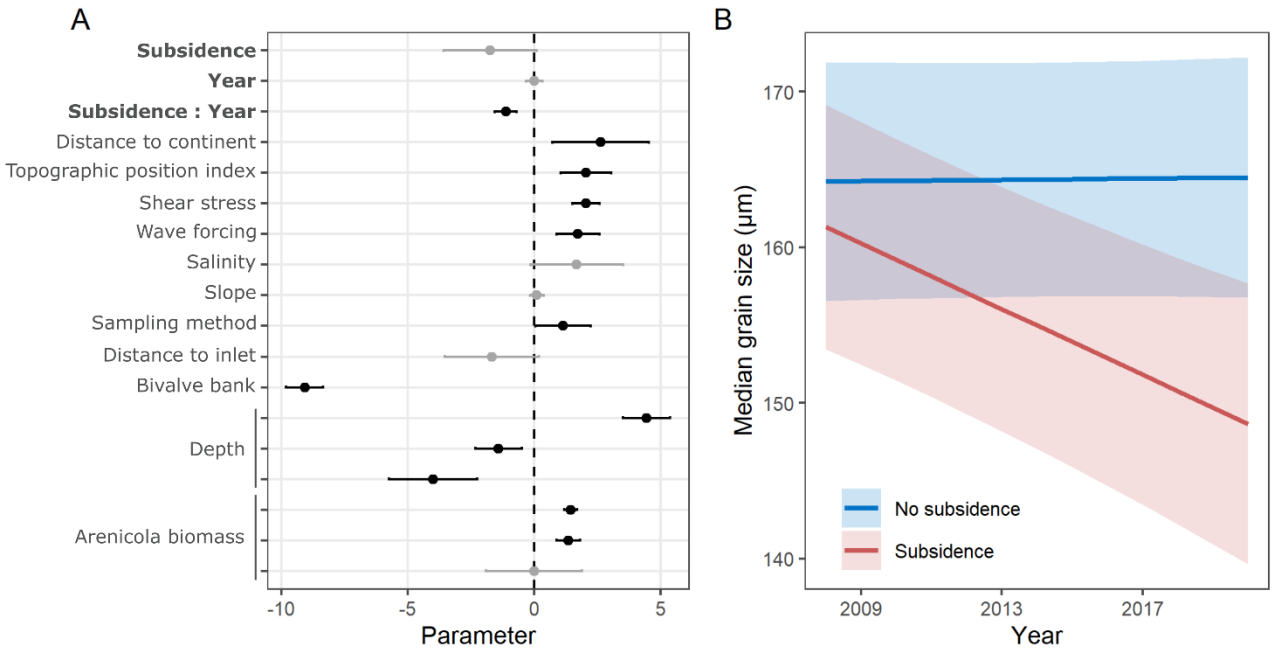


Fig 2: Results for the sediment median grain size model. **A.** Parameter estimates for covariates (mean ± 95% CI). Covariates for which a smoother was applied have more than one parameter. Points and lines in black show effects that are different from zero with 95% confidence. **B.** Mean and 95% confidence intervals of median grain size, within and outside the subsidence area throughout the study period.

Mud fraction

On average, samples contained 0.13 ± 0.13 fraction of mud (mean ± sd). Mud fraction was negatively affected by most of the covariates assessed, but positively affected by bivalve bank presence and wave forcing (Fig 3 A). We found a positive effect of subsidence on the mud fraction (Fig 3A) that remained constant in time (Fig 3B). On average, the mud fraction within the subsidence area was 0.03 higher than in the rest of the Wadden Sea.

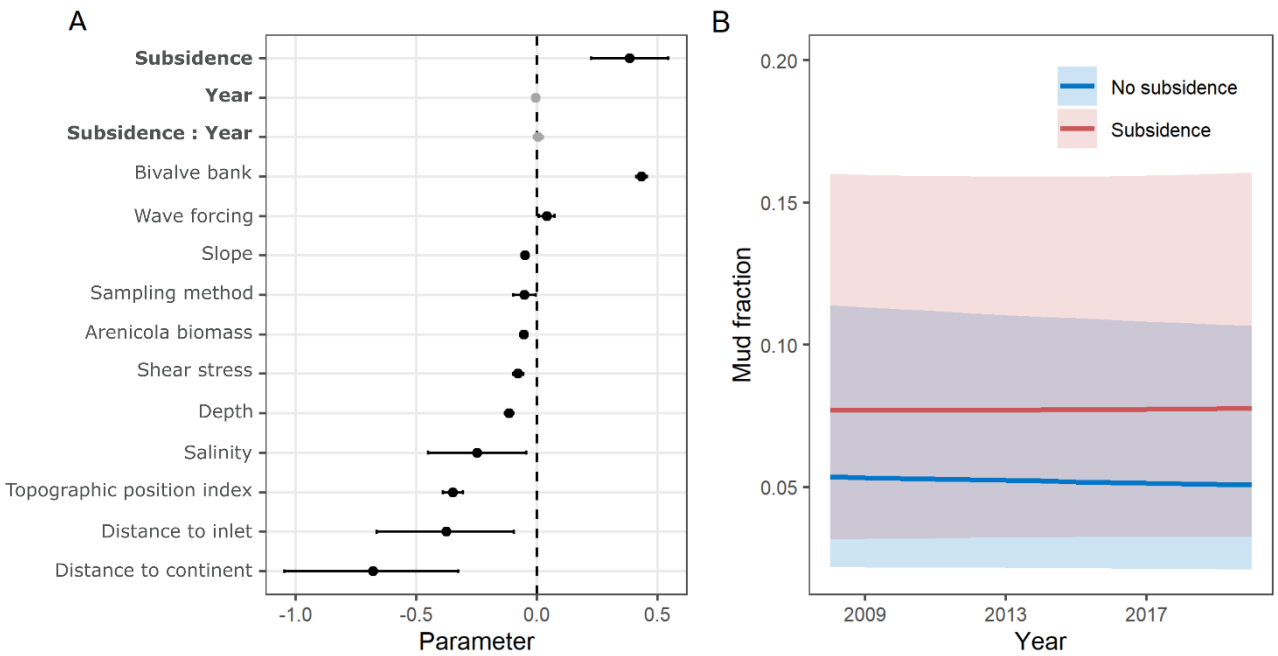


Fig 3: Results for the total sediment mud fraction model. **A.** Parameter estimates for covariates (mean ± 95% CI). Points and lines in black show effects that are different from zero with 95% confidence. **B.** Mean and 95% confidence intervals of mud fraction, within and outside the subsidence area throughout the study period.

Biomass

We found an average biomass of 24.5 ± 45.3 g m^{-2} (mean ± sd). Biomass was positively affected by wave forcing and negatively affected by distance to tidal inlet, current shear stress and slope (Fig 3A). Depth and day of the year had non-linear effects on biomass (Fig 3B). We did not find an effect of subsidence on total

biomass of the macroinvertebrate community throughout the studied period (Fig 3C), but there was a negative trend within the subsided area and a slightly positive trend outside (Fig 3D).

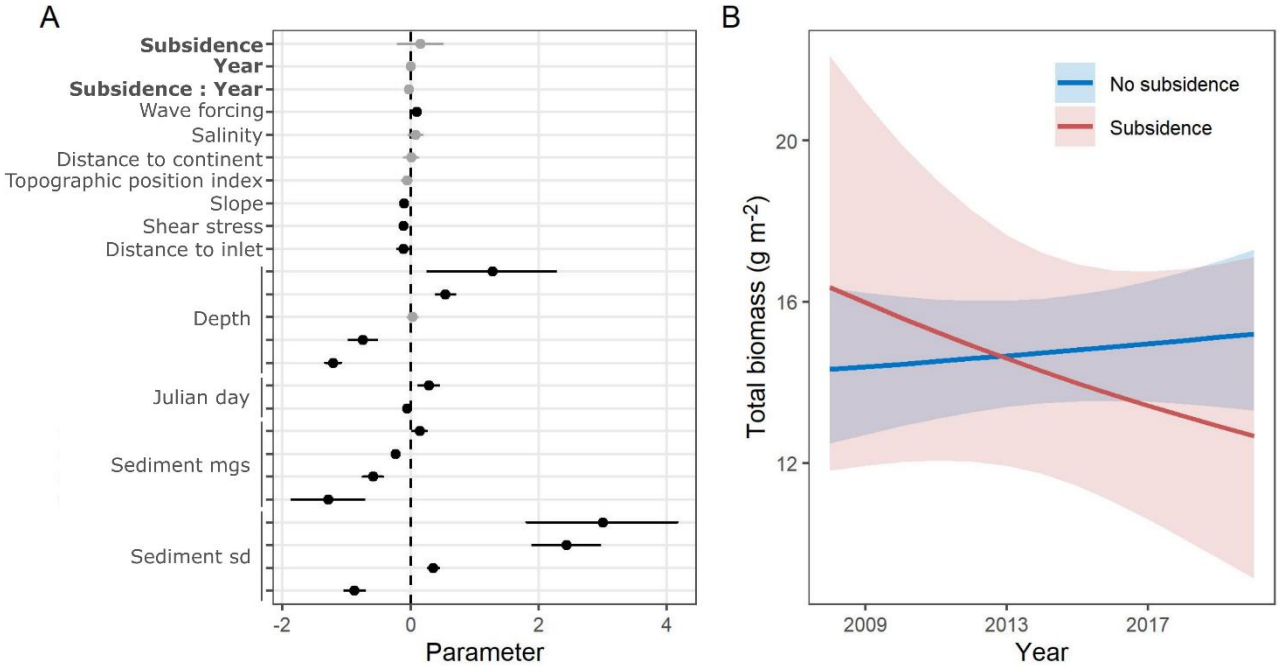


Fig 4: Results for the total biomass model. **A.** Parameter estimates for covariates (mean ± 95% CI). Covariates for which a smoother was applied have more than one parameter. Points and lines in black show effects that are different from zero with 95% confidence. **B.** Mean and 95% confidence intervals of biomass, within and outside the subsidence area throughout the study period.

Species-specific effects of land subsidence

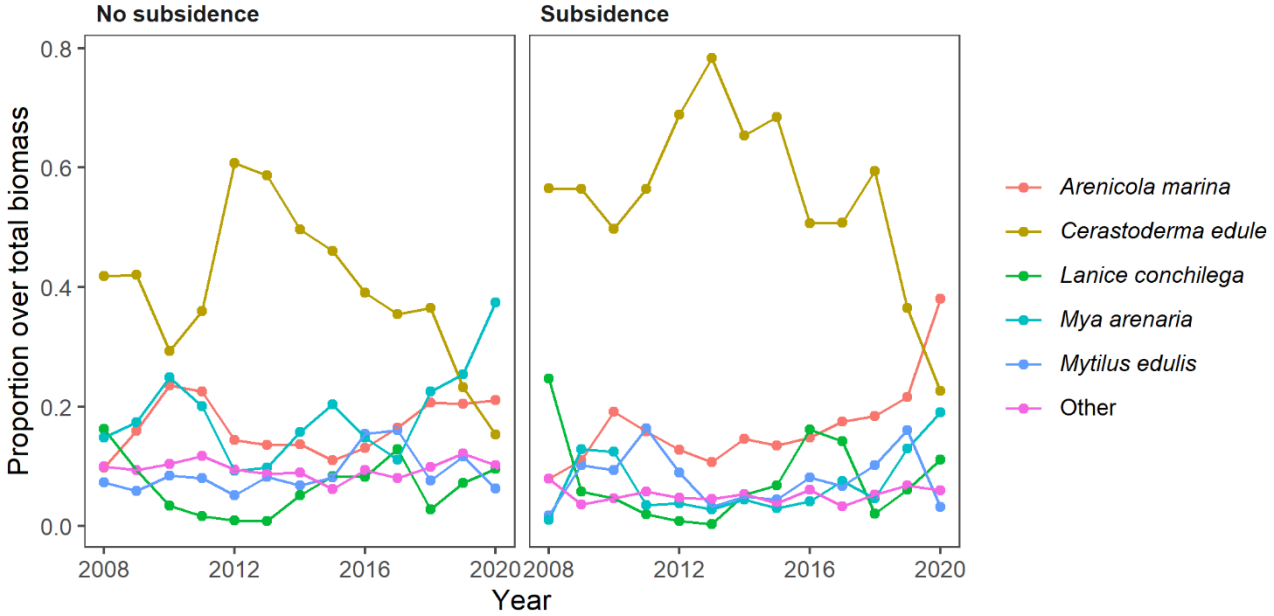


Fig 5: Relative contribution of species to overall biomass within and outside the subsidence area. The portrayed species are the ones with higher contribution to biomass within the subsidence area.

The most abundant species (in terms of biomass) within the subsidence area were *Arenicola marina*, *Cerstoderma edule*, *Lanice conchilega*, *Mya arenaria* and *Mytilus edulis*. These species also represented an important fraction of biomass outside the subsidence area, with other species only contributing up to 5 ± 1% of total biomass (Fig 5). From 2008 to 2019, *C. edule* was the species with highest biomass in both areas, however, its contribution was higher within the subsidence area. *C. edule* represented the 56% of total biomass within the subsidence area in 2008, but only the 40% outside. In 2020, *C. edule* was surpassed by *A. marina* in both areas, and by *M. arenaria* outside the subsidence area (Fig 5).

With the mixed-effects model, we found differences in population trends within and outside the subsidence area, and these differences depended on the 'depth use' of species (Fig 6). For species that use deeper areas, populations have increased in biomass within relative to outside the subsidence area. On the contrary, for

species that use shallower areas, populations have been slightly decreasing within relative to outside the subsidence area (Fig 6).

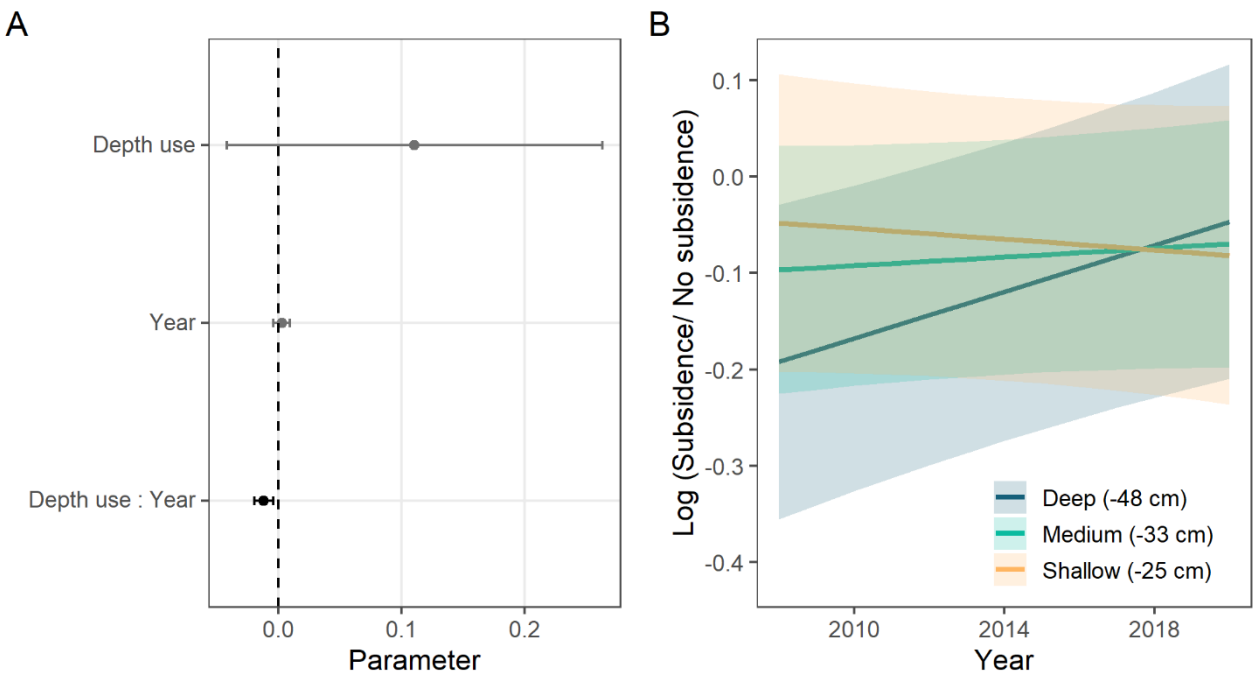


Fig 6: Results for the population trends model. **A.** Parameter estimates for covariates (mean ± 95% CI). Points and lines in black show effects that are different from zero with 95% confidence. **B.** Mean and 95% confidence intervals of the ratio of biomass within and outside the subsidence area throughout the study period.

Discussion

We found a change in sediment composition within the land subsidence area relative to outside. After accounting for confounding environmental variables, median grain size within the subsidence area decreased by 10% during the study period and the mud fraction was 3 percentage points higher throughout. These changes do not seem to significantly affect the total biomass of the macroinvertebrates living there,

but there was a negative trend. Moreover, we did detect a significant increase of species that use deeper habitat, suggesting changes at the community level.

The Wadden Sea is a complex and dynamic system, and therefore, it is difficult to establish a cause-and-effect relationship between changes in sediment (or species) composition and land subsidence. Subsidence occupies an area with unique characteristics in the Wadden sea, and any change in the subsidence area could be caused by other natural or anthropogenic processes, raising the issue of a lack of a proper control in this study, a problem inherent to nearly all ecological field studies. To attribute causation, a BACI design is necessary (Green 1979). Furthermore, subsidence has been going on long before we started collecting the data, so using the initial conditions (i.e. data from 2008) as the control would be incorrect. However, median grain size, mud fraction and biomass are not randomly distributed in space, rather their distribution results from environmental and biological processes that we aimed to capture through the covariates (like depth and bed level shear stress of currents) in the statistical model. Because the range of all the covariates within the subsidence area fall within the range of the whole Wadden Sea's (see histograms in Table 1), we can attempt to detect differences “over and above” these processes between the subsidence area and the rest of the Wadden Sea. On top of this, the addition of a spatial latent field with a temporal structure allows us to control for spatially and temporally structured errors caused by historic events and missing covariates. Even after accounting for confounding environmental variables and residual spatiotemporal patterns, we still observed differences in median grain size and mud fraction within and outside the subsidence area.

Subsidence has not affected the average bathymetry and morphology of the tidal flats (van der Vegt 2022), which implies that sedimentation was so far able to keep up with subsidence. However, within the subsidence area median grain size was decreasing, and the overall mud fraction was smaller throughout the study period. Modelled deep subsidence is bowl-shaped, with deeper parts in the centre and shallower parts on the edges of the subsidence contours. Sediment tends to be smaller in troughs (e.g. Mestdagh et al. 2020) so the bowl-shaped area could therefore result in a smaller-than-expected sediment pattern. It is possible

then, that we are detecting the effects of subsidence on sediment composition, while changes in bathymetry or morphology might be too subtle or compensated too fast to be detected.

Mud fraction was higher within the subsidence area in the beginning of the study and remained stable, showing a different pattern than median grain size. This indicates that the decrease in median grain size is due to an increase of small sand rather than an increase in mud fraction. The different patterns in mud fraction and median grain size might be the result of mud and sand deposition being governed by independent mechanisms (Colina Alonso et al. 2021). Furthermore, because subsidence has been going on since the eighties (Fokker et al. 2018), these differences could very well be the result of the accumulation of long-term effects: it is possible that the effects over mud fraction have plateaued, while the sand fraction has been more recently affected.

We did not find statistical differences in total biomass within and outside the subsidence area, but a decreasing trend within was observed. It is possible that this trend is due to the prevalence of *Cerastoderma edule* within the subsidence area. Both, within and outside, this species decreased in biomass during the study period, but biomass within the subsidence area showed a larger drop. The reasons behind this pattern need further study, but the habitat-use analysis shows that *C. edule* is one of the species that uses shallower areas, and that species using shallower areas are decreasing in biomass within the subsidence area relative to outside.

Species that increase within the subsidence area, relative to the outside, are those that use deeper areas. Because these are most species, this results in a counter-intuitive pattern, in which most species increase within the subsidence area relative to outside, while at the same time total biomass within the subsidence area shows a decreasing trend. There is another counter-intuitive pattern: median grain size is getting smaller within the subsidence area and, simultaneously, species that use deeper areas – often with coarser sand – are doing better within the subsidence area relative to outside. Due to the interdependency of depth and sediment composition, species that use deeper areas are generally those that use coarse sediment. With this study, we cannot tell if species are choosing for a specific sediment or for a specific depth, but these

patterns might be the result of tidal flats sinking in some places while getting higher in others within the subsidence area, despite the average elevation being unaffected (van der Vegt 2022).

The Wadden Sea as a UNESCO heritage site is a protected area. Information collected with SIBES together with statistical tools as those used in this study, could also prove useful to assess the impacts of other human activities in the area. For example, there are other areas that were or are subject to anthropogenic subsidence in the Wadden Sea (Fokker et al. 2018). These were not included in the present study because the information available is not comparable, but applying the methods described here might give us a better idea of the effects that these and other human activities might have. Furthermore, where human activities have started after the beginning of the monitoring program, SIBES could be used to perform proper "before, after – control, impact" studies to study causation.

The gas extraction near Ameland is managed following the "hand on the tap" principle, meaning that "if the natural values of the Wadden Sea are compromised", gas extraction must be reduced or even cease. Intertidal area loss is the most evident threat posed by subsidence, so concrete thresholds have been established to prevent it (6 mm y^{-1} for the saltmarsh area, National Project Decree 2005). Other threats posed by subsidence to "natural values" would also warrant the adjustment of gas production (National Project Decree 2005), but in those cases three problems might hinder the effective implementation of the "hand on the tap" principle. Frist, the lack of definition of what the Wadden Sea's natural values are. Are sediment and community structure natural values? Second, the lack of guidelines about what constitutes an effect. Here, we show effects on sediment and community composition might be in place, but the lack of measures from before the beginning of gas extraction precludes us from attributing causality. This does not mean that effects do not exist, but rather that it is not possible to unambiguously prove them. To do proper monitoring of potential effects, before-after control-impact studies are essential. The third problem is the lack of a threshold for these effects that would warrant management consequences. If the 1 µm y^{-1} decrease in median grain size is indeed caused by gas production, does this warrant management consequences? Could this be considered a threat to the natural values of the Wadden Sea? For a successful implementation

of the “hand on the tap” principle it is necessary to clearly define concepts and thresholds beforehand, otherwise the water will continue to run regardless of where the hand is.

Author contribution

Allert Bijleveld and Geert Aarts conceived the idea. Allert Bijleveld, Geert Aarts and Paula de la Barra designed the methodology. Paula de la Barra analyzed the data; interpretation of results was discussed by all three authors. Paula de la Barra led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Conflict of Interest

SIBES is currently partly financed by the Nederlandsche Aardolie Maatschappij NAM, which exploits the area for gas production generating the land subsidence studied here.

Data availability statement

Data will be available at NIOZ Data Archive System upon publication.

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