The conservation of eroding intertidal flats through nourishments: Ecological development on the Oesterdam tidal flat (Oosterschelde, the Netherlands)

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Abstract

In December 2013 350000 m^3 sand was nourished on the Oesterdam intertidal flat in the Oosterschelde (The Netherlands), in order to counteract the erosion of the tidal flat. The nourishment consisted of a hook-shaped nourishment; part of the sand was placed directly near the Oesterdam dike as additional coastal protection (called dyke foot nourishment). The hook-shaped part of the nourishment (called main sand nourishment), aimed to protect and slowly feed the central (i.e. undisturbed) tidal flat with sediment, and was constructed lower in the intertidal zone. The nourishment initially killed all benthic life, and the recovery of the benthic macrofauna was monitored over a three-year period (2014 – 2016), and compared to the benthic community observed on the central tidal flat. The Oesterdam nourishment showed a fast recolonization of benthic macrofauna. After one year (2014) already species richness and abundance was similar or higher on the nourished areas, although biomass on average was still lower compared to the undisturbed central tidal flat. The following years (2015, 2016) the recovering community still differed from the ambient, undisturbed, sediments due to enhanced recruitment success of long-lived species (i.e. bivalves *Cerastoderma edule* and *Limecola balthica*), presumably resulting from the lowered interference from bioturbation during early recovery stages in the nourished areas. Also the non-indigenous bivalve *Ruditapes philippinarum* colonized the nourished areas.
Recolonization appeared patchy on the nourishment, with large spatial variability. Some areas could be identified as ecological hotspots with a high ecological richness; these areas were situated in the more sheltered, lee side of the main sand nourishment and dyke foot nourishment. Here, high densities of cockles *Cerastoderma edule* and mudsnails *Peringia ulvae* were observed. In the same areas also a mussel bed (*Mytilus edulis*) and several sea grass (*Zostera noltii*) patches were observed in 2017. Other areas were identified as ecological coldspots with a low ecological richness; these were the more exposed areas on the main sand nourishment and the dyke foot nourishment. Also the nourishment had an indirect effect on the benthic community of the undisturbed central tidal flat, as ecologically rich areas were created at the lee side of the main sand nourishment, for instance promoting the settlement of cockle *Cerastoderma edule*.
With respect to birds, Oystercatchers and Eurasian Curlews used the Oesterdam as foraging area, including the nourished areas (especially the main sand nourishment). Other wader species such as

Dunlins and Redshanks were hardly observed, although they were frequently seen foraging south of the Oesterdam study area. The relatively fast recolonization of the benthic macrofauna, and especially the occurrence of several bivalve species and *Peringia ulvae* should be profitable for waders like Oystercatcher and Knot. Disturbance by humans could be one explaining factor, as the area is frequently used for bait digging, walking and kite surfing. These activities are allowed but are considered as a threat to the area with respect to its function as foraging area for waders.
Three years of monitoring the recolonization and recovery of the benthic macrofauna is still short, and the long-term evolution (> 5 years) of the benthic macrofauna needs to be assessed to determine the exact functioning of this area as foraging ground for birds.

Keywords: benthic macrofauna, nourishment, recovery, waders, sediment

Introduction

Intertidal flats and shoals are intertidal, non-vegetated, soft sediment habitats, found between mean high water and mean low water spring tide (Dyer et al. 2000) and are generally located in meso- and macrotidal estuaries and other low energy marine environments. They are distributed widely along coastlines world-wide, accumulating fine-grain sediments on gently sloping beds, forming the basic structure upon which coastal wetlands build. The morphology of intertidal flats is a complex outcome of tides, waves, sediment properties and ecological processes (Le Hir et al. 2000, Friedrichs 2011).

Intertidal flats are productive components of shallow coastal ecosystems providing essential ecosystem functions and services: recycling of organic matter and nutrients from terrestrial and marine sources, primary production, sustaining benthic organisms that are food to many fish and waterbird species (Heip et al. 1995, Herman et al. 1999, Ysebaert et al. 2000). Because of this, tidal flat ecosystems are worldwide protected by international conventions and legislations, e.g. the Ramsar convention for the protection of migratory birds or the European Natura2000 legislation. Intertidal flats, along with seagrass beds, saltmarshes and mangroves constitute coastal wetlands, a vital part of the coast. In this complex, tidal flats form a buffer zone between deeper channels and the higher-lying vegetated habitats, protecting the latter by dissipating wave energy.

Despite their services and protection, intertidal flats are under pressure from human-induced changes that affect their quantity and quality (Lotze et al. 2006, Airoldi and Beck 2007). At a global scale, climate change and sea level rise on the one hand, and human coastal development on the other hand, squeeze the intertidal coastal strip. At the scale of whole basins, embankments, building of barriers and dredging activities have induced changes in geomorphology and hydrodynamics that affect morphology, biodiversity and ecological value of the intertidal area (e.g. Thrush et al. 2004). At the scale of the individual flat, land reclamation, artificial saltmarsh development and dike reinforcements have provoked considerable losses. As an example of system-wide management effects, intertidal flats in two adjacent estuarine systems in SW Netherlands (Oosterschelde, Westerschelde) evolved differently over the past decades (de Vet et al. 2017). The Oosterschelde storm surge barrier decreased tidal range and tidal velocity, which caused erosion and flattening of the tidal flats in the Oosterschelde. By 2100 less than half of the tidal flat area will remain in the Oosterschelde (de Ronde et al. 2013). In contrast, deepening and widening of the Westerschelde navigation channel caused heightening and steepening of the tidal flats (de Vriend et al. 2011). Underlying is a feed-back between hydrodynamics, sediment dynamics, and tidal flat morphology that is still badly understood. However, it has far-reaching consequences for the benthic animal and plant species inhabiting these flats, with redistributions and changes in species community as a consequence (van der Wal et al. 2012, Cozzoli et al. 2013). Both these morphological and ecological changes most likely also affect higher trophic levels, such as birds that use these tidal flats as foraging grounds during low tide. Both Oosterschelde and Westerschelde are areas that accommodate internationally important numbers of several bird species like Oystercatcher, Knot, Grey Plover, etc. These birds use these areas during their migration and wintering periods.

As a measure to mitigate the erosion of intertidal flats in the Oosterschelde, the Dutch government (Rijkswaterstaat) started with pilot experiments nourishing the tidal flats with sand. Compared to beach nourishments, the nourishment of tidal flats in estuarine or coastal environments is relatively unexplored. In recent years, however, dredged material has become regarded as a potential resource and used to create and/or improve intertidal habitats (so-called beneficial use schemes) (Ray 2000, Bolam and Whomersley 2003). Relocation of dredged material from ports and navigation channels to recharge or recreate intertidal habitats is proposed as a measure to derive environmental benefits in several estuaries worldwide (Bolam 2014).

Ideally, (1) the nourished sediment stays in place over a long period or slowly feeds adjacent intertidal areas (depending on the goal), (2) is colonized rapidly by benthic life, and (3) quickly regains its ecological value as foraging area for birds (mainly waders) and fish. For wader species abundance and availability of benthic macrofauna, their main food source, are important. The time food is available to waders is to a large extent determined by the time tidal flats are exposed during low tide. Due to the erosion of the tidal flats in the Oosterschelde, feeding time for waders slowly decreases, posing threats to their survival. A nourishment will initially increase the emersion time and therefore the potential foraging time, but at the same time will kill most of the benthic life present. It is the balance between the recovery time of the benthos and the morphological life-span of the nourishment that will determine its suitability as a measure to conserve these tidal flats as foraging grounds for waders. How to reach this goal by varying the nourishment practice is an important practical question, requiring thorough insight in the physics and the ecology of tidal flat developments. The nourishment on the Galgeplaat intertidal shoal in the Oosterschelde (20 ha, 130.000 m^3) was one of the first 'large' scale nourishments (van der Werf et al. 2015). In 2013, the Oesterdam nourishment was executed, a much larger nourishment (34,1 ha, 350.000 m^3) compared to the Galgeplaat, designed partly as a safety buffer in front of the Oesterdam dike and partly as a 'sand engine' that should supply sediment to a much larger intertidal area and by doing so protect this area against erosion. In that sense it differs from the Galgeplaat nourishment, besides the fact that the Galgeplaat is a tidal shoal and the Oesterdam an intertidal flat fringing the dike, as the Galgeplaat nourishment was set-up to evaluate how long a nourishment would stay in place on a tidal shoal and how it would develop ecologically. The Oesterdam nourishment offers a unique opportunity to better understand the behaviour and ecological development of sand nourishments on intertidal flats.

Nourishments will affect the physico-chemical gradients of tidal flats which in turn will influence the distribution and abundance of organisms that inhabit these tidal flats, like microphytobenthos and benthic macrofauna. Changes in exposure time, sediment properties, hydrodynamics (tidal currents, waves) and sediment dynamics all will have an impact on these organisms. However, it remains unclear how changes in tidal flat morphology and related aspects such as shape, slope, exposure, eroding vs accreting state, influence the distribution and abundance of benthic organisms on tidal flats at different spatial and temporal scales. Understanding this relation will allow to better predict the consequence of human interventions to tidal flat eco-morphodynamics and ecological values. Moreover, changes in the physico-chemical gradients along tidal flats that impact the condition and behaviour of key species that are involved in maintaining ecosystem resilience, such as habitat-modifying or ecosystem engineering organisms, have the potential to shift the interactions within an ecosystem, thereby altering ecosystem stability. It is still unknown how this interacts with trends in tidal flat morphology.

In this study, we aim to assess spatial and temporal effects of the Oesterdam nourishment on the intertidal macroinvertebrate community up to three years after establishment. We hypothesize that benthic macrofauna will recolonize the nourished area already after one year but that benthic communities will differ between the nourished areas and the undisturbed area, even after three years. Furthermore, we hypothesize limited impact of the nourishments on the undisturbed central tidal flat after three years. At the same time, we also evaluate the use by waterbirds of the Oesterdam area.

Material & Methods

Oosterschelde

The Oosterschelde estuary, located in the southwest of The Netherlands, is a 351 km^2 semidiurnal tidal basin with tidal flats (118 km^2), deep gullies and shallow water areas. In response to a devastating flood in 1953, a storm surge barrier was constructed at the sea side (finished 1986), separating the estuary from the North Sea; in the same period the eastern part of the estuary was closed off by two compartmentalization dams. The basin area of the Oosterschelde, the tidal prism, the tidal range and the tidal currents decreased as a consequence of these measures. At present, the estuary has a mean tidal amplitude ranging from 2.47 m near the storm surge barrier to 2.98 m in the northern branch and 3.39 m at the southeast end (Nienhuis & Smaal 1994). The maximum current velocity is about 1.0 m s^{-1}. Salinity throughout the estuary is high, generally > 30 psu (Nienhuis & Smaal 1994). Due to the reduction of tidal volume and flow, the Oosterschelde basin is presently not in morphological equilibrium and the oversized channels are in need of sediment. Sediment erodes from the tidal flats into the channels during storms, whereas tidal forces are too small to redistribute the sediment back to the tidal flats (Mulder & Louters 1994); on average, a net erosion rate of 10 mm $year^{-1}$ occurs on the tidal flats (Santinelli & de Ronde 2012). Reduction in tidal flat area and elevation diminishes valuable habitats, impacting bird populations. It also poses a threat to coastal defence as dikes become less protected from waves and currents with the loss of tidal flats in front.

Oesterdam nourishment

The Oesterdam tidal flat is situated in the eastern part of the Oosterschelde (Figure 1, Figure 2) and is connected to the Oesterdam dike. The tidal flat experiences erosion and decreased 25 to 50 cm in height since 1986. A nourishment, placed in front of the dam in November 2013, should mitigate erosion of the flat and extend the life span of the dike and surrounding levees with 25 to 30 years. The nourishment consists of a 350,000 m^3 hook-shaped nourishment, see Figure 1 and Figure 2. Part of the sand was placed directly near the Oesterdam dike as additional protection (called dyke foot nourishment). The hook-shaped part of the nourishment (called main sand nourishment), aimed to protect and slowly feed the central (i.e. undisturbed) tidal flat, was constructed lower in the intertidal zone. The dyke foot nourishment has an area of approximately 15 ha, and was initially constructed with an average height of + 1,55 cm NAP. The main sand nourishment is approximately 2 km long with an area of approximately 27 ha. A lowering is applied in the middle of the main sand nourishment to permit flow of water and restricted flow of sand from the south to the north onto the existing flat. The central tidal flat, i.e. the undisturbed part, covers an area of approximately 36 ha.

The construction took 6 weeks and finished in the last week of November 2013. After the construction, the dyke foot nourishment appeared to be constructed too high by the constructor, resulting in aeolian transport, depositing sand near the dam and on the road that originated from the dyke foot nourishment. To reduce the aeolian transport, a re-profiling of the nourishment section close to the dam was executed in March 2014, resulting in a broader, but lowered dike foot nourishment (average height + 63 cm NAP) (Figure 1 and Figure 2). Additional to the nourishments, four artificial oyster reefs (Figure 2) have been constructed to additionally decrease the erosion of the intertidal area.

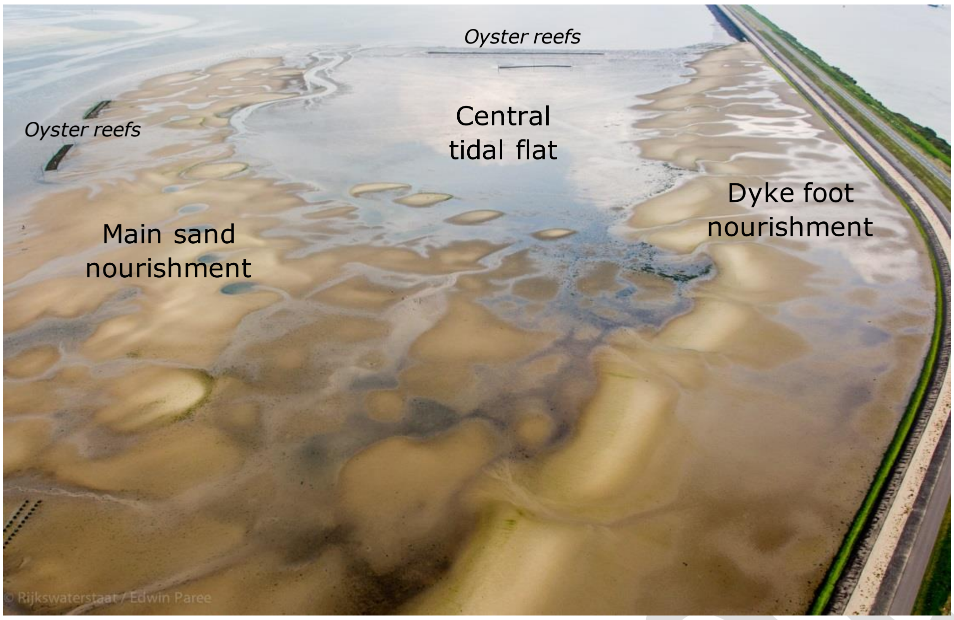


Figure 1. The Oesterdam nourishment with the different subareas indicated.

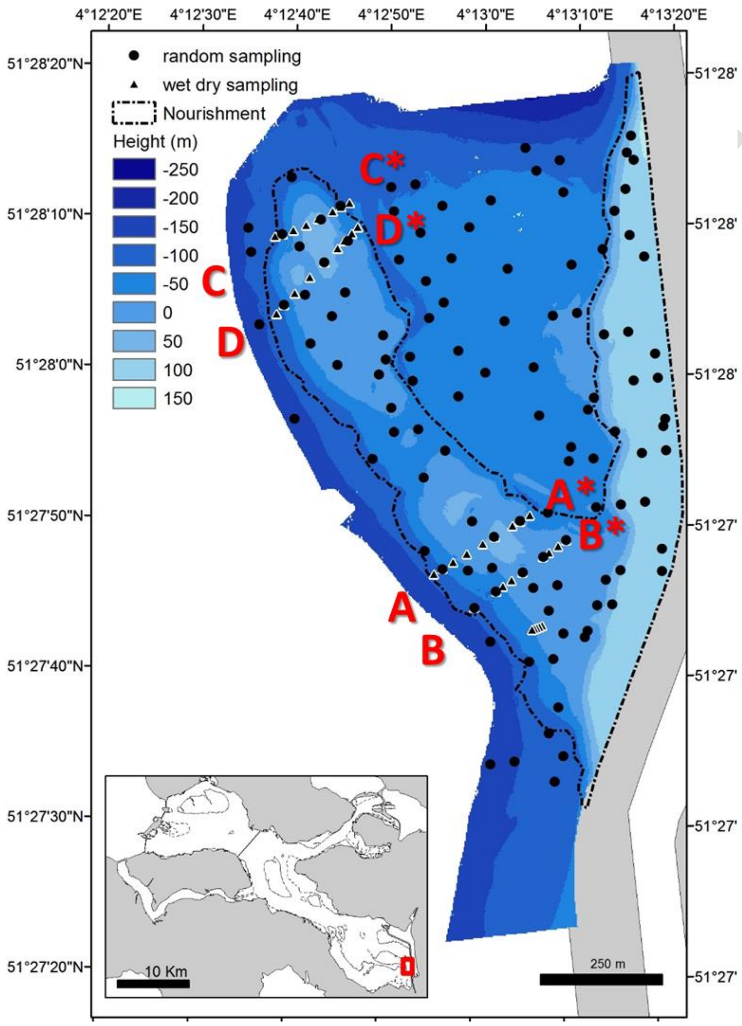


Figure 2. Sampling stations for benthic macrofauna (black dots and the four transects A-A*, B-B*, C-C*, D-D*) at the Oesterdam tidal flat, located in the eastern part of the Oosterschelde (inset map). Dashed line indicates the contours of the nourishment. Underlying elevation map (in cm NAP) of November 2014.

Sampling

Benthic sampling and laboratory analysis

To get an indication of the environmental conditions and benthic community composition prior to the nourishment, the Oesterdam tidal flat was sampled on three occasions (Table 1). After the construction of the nourishment, the Oesterdam was sampled in October 2014 (T1), October 2015 (T2) and October 2016 (T3) (Table 1). In total 114 sampling locations (Figure 2) were sampled to evaluate the recolonization of the benthic macrofauna on the nourishment in comparison to the benthic community composition on the undisturbed, non-nourished central area.

Table 1. T_0 (May 2012, October 2012, April 2013), T_1 (October 0214, T_2 (October 2015) and T_3 (October 2016) sampling for elevation, sediment grain size and benthic macrofauna at the Oesterdam. N = number of sampling stations.

Sampling date		Elevation	Sediment grain size	Benthic macrofauna
May 2012	T_0	58	59	21
October 2012	T_0	-	56	20
April 2013	T_0	-	56	20
October 2014	T_1	114	114	114
October 2015	T_2	114	114	114
October 2016	T_3	114*	144	114

*Elevation was measured in May 2017.

For each sample station the following abiotic environmental variables were collected: elevation, sediment characteristics (grain size, mud content, chlorophyll *a*), current velocities and bottom shear stress. Elevation measurements were conducted using a differential GPS device with a horizontal and vertical measure accuracy of 8 and 13 mm, respectively (Leica GS12, Leica Geosystems AG, Switzerland, correction signal: SmartNet, Leica Geosystems, the Netherlands). Elevation was expressed in m NAP, where NAP is Dutch Ordnance Datum, which is about mean sea level. From the elevation emersion time was calculated for each sampling station, using water levels from the nearby gauge station Marollegat.

At each station sediment was taken from the upper 3 cm of the sediment using a 3.0 cm diameter syringe. Samples were wet weighted, freeze-dried, and dry weighted before median grainsize (d_{50}, in mm) as well as the size distribution (percentage coarse, medium, fine and very fine sand, and silt) were determined using a Malvern particle sizer. Additional, Chlorophyll *a*, as a measure for food availability for benthic animals, was measured by three pooled sediment samples collected from the upper 1 cm of the sediment, using a 1 cm diameter syringe. Chlorophyll samples were analysed for 95 sampling stations each year. The samples were stored in the dark at -80°C, after which they were analysed spectrophotometrically according to Aminot and Rey (2002).

To quantify the macrobenthic community structure, three 10 cm diameter cores, extending 30 cm into the sediment, were taken at each sampling station. Cores were pooled and sieved through a 1 mm mesh. Macrofauna retained on the sieves were preserved in buffered formaldehyde solution, stained with Rose Bengal, sorted and identified to the lowest possible level. Biomass was estimated based on the wet weight of the individuals. Ash free dry weight (AFDW) was subsequently determined using existing conversion factors. Additionally, *Arenicola* castings, subdivided into small (junveniles) and big (adults), were counted within 0.25m^2 quadrant (n=10) at each sampling station.

In addition four transects on the main sand nourishment were sampled to gain insight in the small-scale spatial changes on the nourishment (Figure 2). Elevation and grain size were measured on four occasions (April 2014, September 2014, September 2015 and September 2016), and benthic macrofauna was sampled and analysed in September 2015.

Besides the detailed benthic sampling at the above mentioned sampling stations, an area-wide mapping of different benthic parameters was done. An area-wide raster (50x50m) was being applied, and on the crossings a visual inspection was made of different, in the field identifiable, benthic macrofauna species present. For species like the lugworm (*Arenicola marina*), the sand mason worm (*Lanince conchilega*) and the periwinkle (*Littorina* spp.) the surface area was inspected, for deeper living species like *Hediste* spp., etc. the sediment was digged out and their presence noted. A quadrant of 50x50 cm was used to count *Arenicola* castings and to search for cockles (*Cerastoderma edule*) by hand raking. In addition, the presence of silt and the depth of the oxidation layer was recorded. These data were collected by Rijkswaterstaat (CIV, Mobiel Meten, Team Zee en Delta).

Bird observations and human disturbance

Bird surveys took place in the winter months in the period November 2014 till January 2017. Bird counts were performed during low tide, till November 2015 on two consecutive days, afterwards on one day (Table 2). The birds were observed using a telescope (25-60x) and a binocular (8x). The Oesterdam was divided in nine different count plots. Birds were counted at pre-determined reference points from a car, to keep disturbance at a minimum. Bird species were noted and individuals were counted inside each plot (Appendix 1). Bird counts were repeated on average seven times during one survey, within a timeframe of two hours before low-tide until three hours after low tide. Distinction was made between foraging and non-foraging birds. Here average numbers of birds counted around low tide, using the three counts centred around the low tide period, are presented.
The study area is also used for recreational purposes. The dike has a bicycle route and the area is a popular kite and windsurfing spot. The area is also a so-called 'spit' location where recreational fishermen are allowed to dig for their bait, mainly lugworms (*Arenicola marina*). People are allowed to walk on the mudflat, and in summer many tourists sit along the dike. During the bird counts also disturbances and recreational use was recorded.

Table 2. Bird counts on the Oesterdam.

Month+Year	*Number of days counted*
nov-14	2
dec-14	2
jan-15	2
feb-15	2
apr-15	2
okt-15	2
nov-15	2
dec-15	1
jan-16	1
feb-16	1
mrt-16	1
apr-16	1
nov-16	1
jan-17	1

Statistical analysis

Density and biomass of benthic macrofauna were expressed per m^2. Species richness was expressed as the total number (sum) of taxa in a sample. To meet the statistical assumptions values for macrobenthic biomass, density and species richness were log-transformed as ln(x+1). Since biomass, density and species richness were correlated, but with some degree of variation, the three variables were standardized and combined into a relative integrative univariate measure of ecological richness for each sample (Ysebaert et al., 2009), defined as $\frac{\frac{(B-\bar{B})}{sd(B)}+\frac{(D-\bar{D})}{sd(D)}+\frac{(S-\bar{S})}{sd(S)}}{3}$, where B is log-transformed biomass, D is log-transformed density and S is log-transformed species richness of benthic macrofauna, averages are denoted with bars and sd is the standard deviation. Ecological richness is used here as an additional univariate ecological indicator. Its value centers around 0 (by definition) for average ecological richness in a given data set, and for our data set ranges from -3.69 (low ecological richness) to 2.52 (high ecological richness). Thus, ecological richness is a relative measure and used here to express differences in macrofauna richness *within* the Oesterdam.

To show the differences in benthic community composition among different subareas, the study area was divided in three main subareas:

- Main sand nourishment (n=43)
- Dyke foot nourishment (n=21)
- Central tidal flat, i.e. the undisturbed central part (n=36)

The distinction between the dyke foot nourishment and the main sand nourishment was motivated by the significant difference in elevation of both areas, with the dyke foot nourishment being considerably higher compared to the main sand nourishment. Fourteen sampling locations do not belong to one of these subareas, but were situated more to the west, or more to the south, and were left out of the statistical analysis. One-way ANOVA was used to analyse differences between the three subareas for each year separately.

A multivariate analysis was performed to assess the community structure of the benthic macrofauna. To avoid ambiguity, specimens that had only been determined at class or phylum level were left out for the multivariate analysis of the community composition. Nemertea and Oligochaeta were included. If not all specimen of a genus were identified at the species level, they were merged to the genus level. The species name was then added in parentheses when only one species was identified within the genus in all samples, whereas *spp.* was used when multiple species were present. Rare species were also omitted from the multivariate analyses (< 1%). As a result, 43 taxa were included in the multivariate analyses. The community structure was analyzed using multivariate statistics in the software package PRIMER, version 7 (Clarke & Warwick, 1994). A Bray-Curtis similarity matrix was constructed from fourth root-transformed density of the macrobenthic taxa. A Non-metric multidimensional scaling (NMDS) was applied to the similarity matrix to represent, as closely as possible, the pairwise (dis)similarity between objects in a two-dimensional space. NMDS is a rank-based approach. This means that the original distance data is substituted with ranks. Analysis of similarities (ANOSIM) was used to test statistically whether there was a significant difference between two or more groups of sampling units, in this case the three years (2014, 2015, 2016) and the three subareas (central tidal flat, main sand nourishment and dyke foot nourishment) . ANOSIM operates directly on the dissimilarity matrix.

To identify significant spatial patterns in ecological richness, spatial cluster analysis based on Anselin Local Moran's I statistic was performed in ArcGIS 10.5 (Anselin 1995). Local Moran's *I* index, *z*-score, *P*-value, and cluster/outlier type were calculated for each sample location to indicate whether the apparent similarity (spatial clustering) or dissimilarity (spatial outlier) was more pronounced than one would expect from a random distribution. A significant high positive z-score for a sample station indicated that the surrounding sample stations had similar values (either high values, i.e., hotspots or low values, i.e. coldspots). Spatial relationships were conceptualized using an inverse Euclidean distance function, with no maximum distance set.

Results

Characterisation of the Oesterdam tidal flat before nourishment (T_0)

The Oesterdam tidal flat is characterized by a gentle slope, with height ranging between -1,50 m NAP and -0,4 m NAP, with the largest part below -1 m NAP. The average height measured in May 2012 on the 59 stations is -0,93 m NAP. The sediment on the Oesterdam can be characterized as fine sand (125 – 250 µm), with little variation between the three periods considered. In the southern part a small area with finer sediment is present.

Table 3. T_0 characterization of the Oesterdam tidal flat for elevation (Z in m NAP), median grain size (D20) and fraction fine sand (Fines).

Variable	*Unit*	*Average*	*SE*	*Min*	*Max*
May 2012 (n=59)					
Z	m	-0,93	0,04	-1,46	-0,36
D50	µm	179	2,6	115	209
Fines	%	67	1,0	38	77
October 2012 (n=56)					
D50	µm	174	2,7	119	209
Fines	%	66	1,0	40	77
April 2013 (n=56)					
D50	µm	173	3,0	110	209
Fines	%	66	1,1	37	75

Over the three periods a total of 41 macrobenthic taxa were observed, on average 30 taxa per sampling period. The average number of species per station varied between 8,7 and 11,4 taxa, the density was on average 3900 ind.m^{-2} showing little variation among periods (Table 4). The benthic community on the Oesterdam tidal flat typically consisted of a fine sand community with the bristle worm *Scoloplos armiger,* the lugworm *Arenicola marina*, and the amphipod *Urothoe poseidonis* (Table 5) as the most dominant species. The most common bivalves were the cockle *Cerastoderma edule* and *Mya arenaria*, the most common gastropod was the mud snail *Peringia ulvae*.

Table 4. Species richness and density on the Oesterdam in May 2012 (n=21), Ocotober 2012 (n=20) and April 2013 (n=20). SE = Standard Error.

Variable	*Unit*	*Average*	*SE*	*Min*	*Max*
May 2012 (n=21)					
Species richness	n	8,7	0,59	3	15
Density	(ind/m^2)	3900	627	497	12368
October 2012 (n=20)					
Species richness	n	11,4	0,69	8	19
Density	(ind/m^2)	3836	477	1326	9549
April 2013 2013 (n=20)					
Species richness	n	11,0	0,70	2	15
Density	(ind/m^2)	4012	525	133	7427

Table 5. The ten most common macrobenthic species on the Oesterdam. Occurrence gives the percentage of samples in which the species was observed for May 2012 (n=21), October 2012 (n=20) and April 2013 (n=20) respectively. The density (ind.m-2) gives the average density of the species for the same periods.

Taxon	Phylum	Class	Occurrence	Density
Urothoe poseidonis	Arthropoda	Amphipoda	91/95/85	1642/1366/904
Scoloplos armiger	Annelida	Polychaeta	76/95/95	684/509/648
Arenicola marina	Annelida	Polychaeta	100/85/90	90/35/28
Capitella capitata	Annelida	Polychaeta	71/90/80	104/333/151
Pygospio elegans	Annelida	Polychaeta	71/55/80	101/48/161
Aphelochaeta marioni	Annelida	Polychaeta	43/75/85	344/411/917
Crangon crangon	Arthropoda	Malacostraca	71/25/70	71/10/114
Peringia ulvae	Mollusca	Gastropoda	57/75/50	654/428/487
Cerastoderma edule	Mollusca	Bivalvia	29/50/40	11/18/28
Mya arenaria	Mollusca	Bivalvia	29/80/75	14/184/141

Environmental changes after nourishment

Overall, over a period of three years after the construction, erosion was observed on top of the nourishment (i.e. the highest parts), while deposition can be seen near the edges of the nourishment. The central tidal flat itself was rather stable and no significant bed changes were observed here. After the construction of the nourishment a drainage channel developed behind the main sand nourishment. After 1.5 year the cross-sections of this channel were getting close to an equilibrium stage; the meander bends are migrating in the direction of the ebb flow, indicating an ebb dominance. The average elevation of the central tidal flat (based on the sampling locations) was -0.80 m NAP without significant temporal changes (Figure 3). The sampling locations on the nourished areas had significantly higher elevations ($p<0,001$), with the main sand nourishment having an average elevation of -0.28 m NAP (2014) till -0.31 m NAP (2016), and the dyke foot nourishment +0.57 m NAP (2014) till +0.50 m NAP (2016). The nourished sampling stations, therefore, became lower in elevation, although no significant differences were observed within each area. As a consequence, also emersion time differed significantly among areas, with the sampling stations on the central tidal flat having an average emersion time of 29%, on the main sand nourishment 43% and on the dyke foot nourishment 64%.

The median grain size of the sampling stations on the nourishment was significantly higher compared to the central tidal flat in all three years ($p<0,001$), but was not significantly different between the two nourished areas (Figure 3). The central tidal flat showed an average median grain size of 180 µm, which increased to 185 µm in 2015 and 192 µm in 2016. Also on the nourishment a coarsening was observed over the years, with on the main sand nourishment average values of 275 µm in 2014, 285 µm in 2015 and 296 µm in 2016 and on the dyke foot nourishment average values of 292 µm in 2014, 287 µm in 2015 and 307 µm in 2016. Similar trends are observed for the different sediment fractions (Appendix 2). Coarse sediment fraction (250–500 µm) is hardly present on the central tidal flat, although increasingly observed over time, whereas on the nourished areas it represents 4-8 % on average, which seems to increase over the years, especially on the main sand nourishment. The fine sediment fraction (125–250 µm) dominates the sediment on the central tidal flat, with >65 % on average, but show a decrease over the years. On the nourishments this fraction accounts for 28-37 % on average, showing a decrease over the years, indicating possible washing out of fines. The very fine sediment fraction (63–125 µm) accounts for 10 % on average on the central tidal flat, whereas it is <1 % on average on the nourished areas, and almost completely disappeared in 2016. Silt fraction (<63 µm) accounts for 3-5 % on the central tidal flat, whereas on the nourished areas this is <1 %.

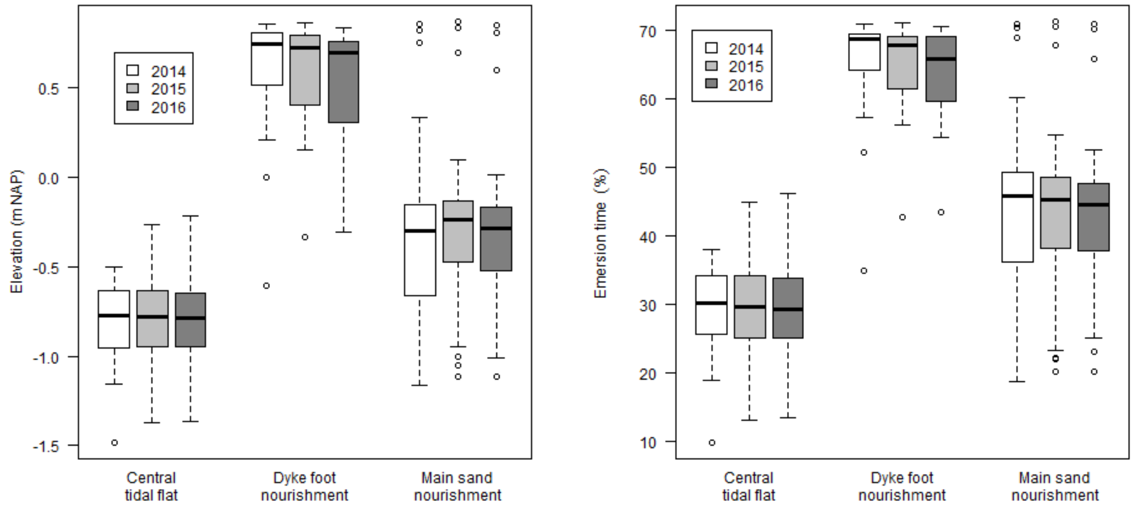


Figure 3. Box-plots of elevation (m NAP) and emersion time (%) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016).

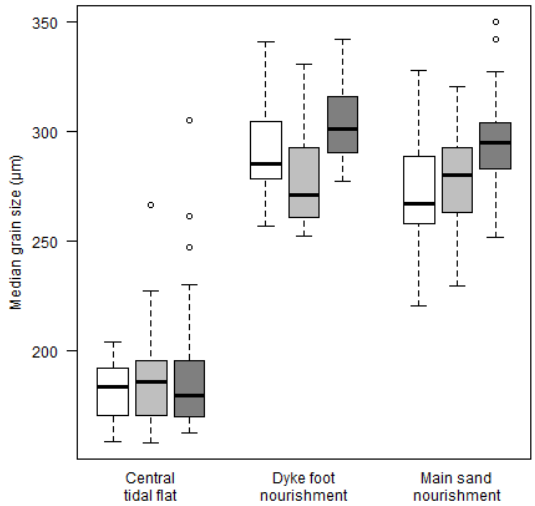


Figure 4. Box-plot of median grain size (µm) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016).

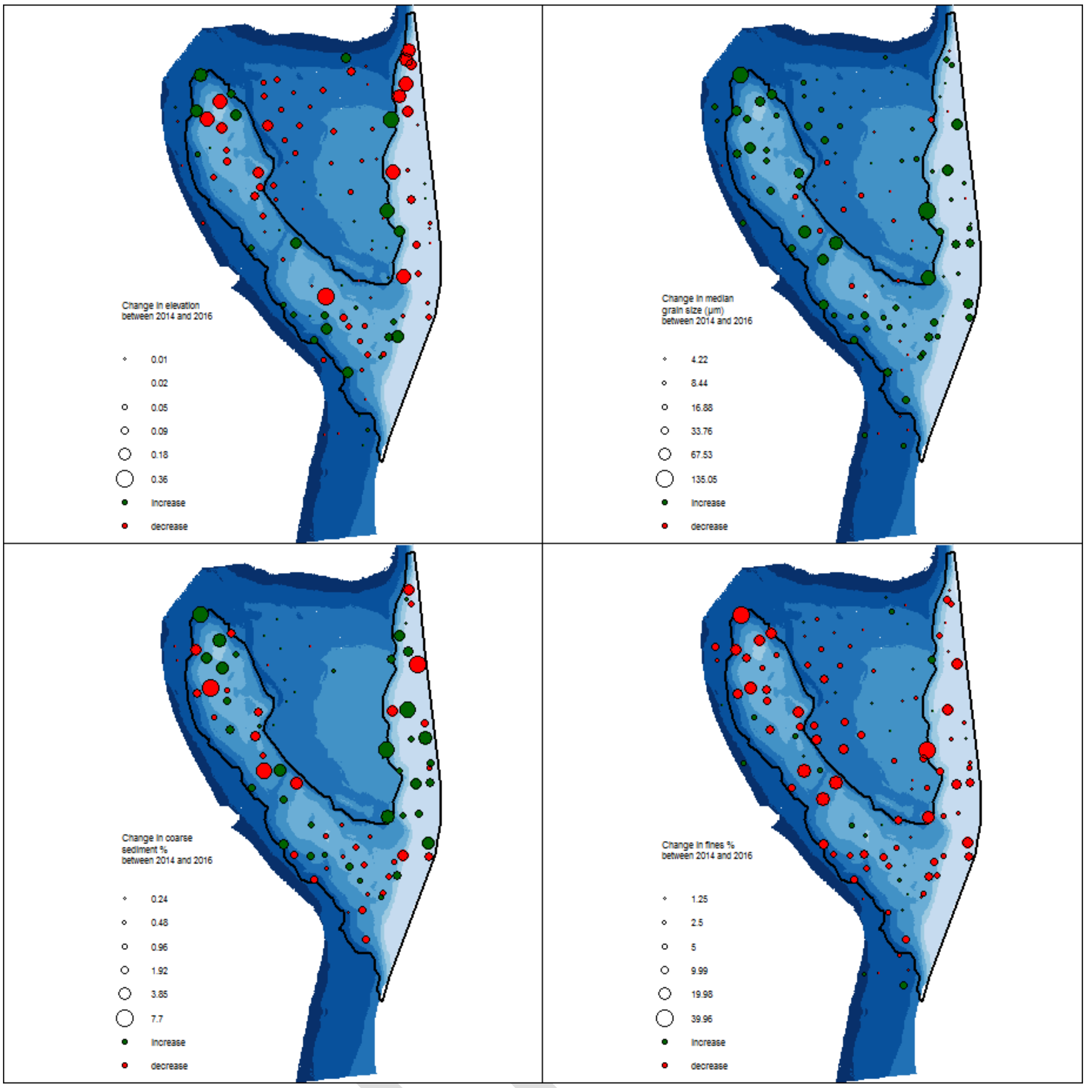


Figure 5. Changes in elevation, median grain size, and the fractions coarse and fine sediments between 2014 and 2016.

Summarizing, sediments on the nourished areas are significantly coarser compared to the central tidal flat, and over time sediments on average became slightly coarser. To visualise spatially these changes, Figure 5 shows the changes between 2014 and 2016 for elevation, median grain size, fraction coarse sediment and fraction fine sediment. Especially some of the highest sampling stations lowered in elevation, and the coarsening of the sediment is also clearly visible with an increase in median grain size at many sites and an overall decrease in the fraction fine sediment.

Chlorophyll *a* in 2014 was significantly higher on the central tidal flat compared to the nourished areas in 2014 ($p<0,001$), and also significantly different between the dyke foot nourishment and the main sand nourishment (Figure 6). In 2015 Chlorophyll was significantly lower on the dyke foot nourishment compared to the central tidal flat ($p<0,02$) and the main sand nourishment ($p<0,001$), but not significantly different between the central tidal flat and the main sand nourishment. In 2016 the central tidal flat again had significantly higher Chlorophyll values compared to the nourished areas ($p<0,001$), which didn't show mutual significant differences (Figure 6).

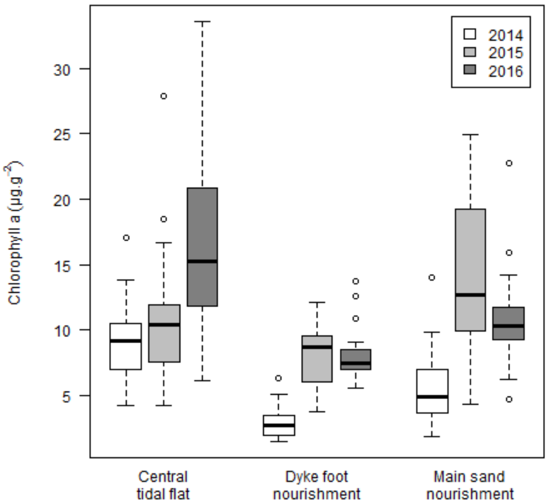


Figure 6. Box-plot of chlorophyll *a* showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016).

Benthic macrofauna changes after nourishment

General changes

The total number of taxa observed in 2014, 2015 and 2016 (n=100 sampling stations each year) was 53, 54 and 53 taxa respectively. The average number of taxa per station varied between the different areas, with in 2014 significantly lower values on the dyke foot nourishment compared to the two other areas ($p<0,001$), which didn't show a significant difference (Table 6). In 2015 the central tidal flat had a significantly higher number of taxa compared to the nourished areas ($p<0,01$). In 2016 there was a significant difference between the central tidal flat and the dyke foot nourishment ($p<0,001$) and between the main sand nourishment and the dyke foot nourishment ($p<0,05$). Average number of taxa per station on the central tidal flat was similar compared to the T_0 situation.

Total density of the benthic macrofauna showed large variation among sampling stations and differed largely between areas and years (Table 6). In 2014 total density was significantly larger on the main sand nourishment compared to the central tidal flat ($p<0,05$). In 2015 and 2016 no significant differences were observed among areas. Total density in general was much higher compared to the T_0 situation, also on the central tidal flat. This was mainly caused by the very high densities of the mud snail *Peringia ulvae*, which was very abundant in the years 2014-2016, especially in 2016. *Peringia ulvae* represented 72% of the total density on the central tidal flat in 2014, and on the nourished areas 93-94%. In 2015 it represented 92% of the total density in all three areas, and in 2016 even 93-98%. Other species are much less abundant, and Figure 7 shows the most dominant species in each year and each area. On the central tidal flat the benthic community was in all three years, in addition to *Peringia ulvae*, numerically dominated by the amphipod *Urothoe poseidonis*, the polychaetes *Scoloplos armiger* and *Streblospio shrubsolii*, and the bivalve *Cerastoderma edule*, but the relative contribution changed between the species. On the dyke foot nourishment also species like *Scoloplos armiger* and *Cerastoderam edule* dominated, but here also other species are observed such as the bivalves *Ruditapes philipinnarum* and *Limecola balthica*, and the amphipod *Bathyporeia* spp. On the main sand nourishment species like the polychaetes *Aphelochaeta marioni*, *Scoloplos armiger* and *Pygospio elegans*, and bivalves like *Ruditapes philippinarum*, *Limecola balthica* and *Cerastoderma edule* numerically dominated. The individual species are discussed in more detail below.

Table 6. Species richness (average number of taxa per sampling station), average density (ind.m^{-2}) and average biomass (g AFDW.m^{-2}) in 2014, 2015 and 2016 on the central tidal flat, main sand nourishment and dyke foot nourishment respectively.

Variable	*Species richness*	*Density*	*Biomass*
2014			
Central tidal flat	10,2 ± 0,57	8869 ± 3146	21,9 ± 7,4
Main sand nourishment	9,9 ± 0,61	34155 ± 7964	14,2 ± 3,5
Dyke foot nourishment	6,0 ± 0,64	12033 ± 2770	5,8 ± 2,8
2015			
Central tidal flat	12,1 ± 0,66	28032 ± 16638	15,6 ± 2,5
Main sand nourishment	8,6 ± 0,51	21352 ± 5367	16,8 ± 1,8
Dyke foot nourishment	8,3 ± 0,87	12697 ± 4340	8,6 ± 4,2
2016			
Central tidal flat	10,1 ± 0,65	36754 ± 13256	20,9 ± 6,7
Main sand nourishment	8,7 ± 0,54	48428 ± 12017	18,4 ± 4,2
Dyke foot nourishment	6,3 ± 0,57	37756 ± 9902	23,9 ± 8,9

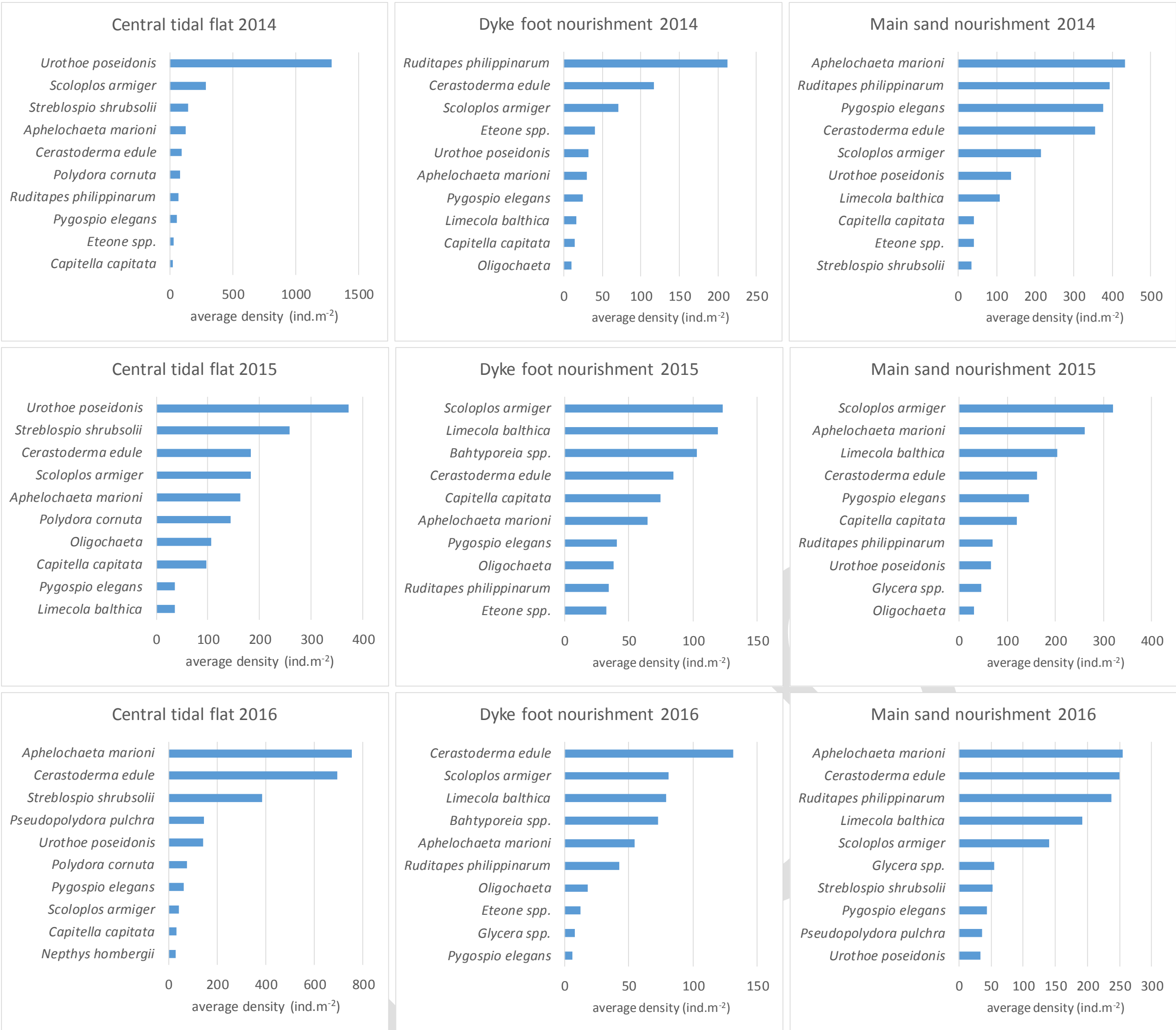


Figure 7. Average density (ind.m^{-2}) of the ten most abundant species (except for *Peringia ulvae*, which was by far the most abundant species, see text) in 2014, 2015 and 2016 on the central tidal flat, dyke foot nourishment and main sand nourishment respectively.

Figure 8 shows the spatial distribution of total density (with and without *Peringia ulvae*) in 2016. *Peringia ulvae* clearly concentrates in the southeast part of the Oesterdam, both on the central tidal flat and on the nourished areas. Without *Peringia ulvae*, high densities are observed in the same area, as well as on certain areas on the central tidal flat, especially behind the lowered area of the main sand nourishment and near the oyster reefs in the north (Figure 8). Lowest densities are observed in the northern parts of the dyke foot nourishment and main sand nourishment.

Total biomass was in 2014 significantly higher on the central tidal flat compared to the nourished areas (Table 6). In 2015 biomass reached similar values on the central tidal flat and the main sand nourishment. In 2016 all three areas showed similar values. *Cerastoderma edule* contributed on average most to the biomass, representing between 23 and 69% of the total biomass (Table 7). Its importance became more important in 2016. The very high densities of *Peringia ulvae* resulted also in relatively high biomass values. *Arenicola marina* had relatively high biomass values in 2014, but its importance dropped over time. The opposite was observed for *Limecola balthica*, that relatively became more important over time, especially on the main sand nourishment. High biomass clusters can be observed in each year, largely corresponding with the densities of the benthic macrofauna (Figure 9). High biomasses were observed in the area where the main sand nourishment connects to the dyke foot nourishment (both on the nourishment as on the central tidal flat, as well as increasingly over the years in the area behind the lowered area of the main sand nourishment. Lowest biomasses were observed in the northern parts of the dyke foot nourishment and main sand nourishment.

Table 7. Biomass of the four most dominant species on the Oesterdam (in g AFDW.m^{-2}). Between brackets the contribution of the species to the total biomass is mentioned.

Variable	*C. edule*	*P. ulvae*	*A. marina*	*L. balthica*
2014				
Central tidal flat	12 (55%)	0,8 (4%)	4,1 (19%)	0,08 (0,4%)
Main sand nourishment	8,5 (60%)	2,2 (15%)	1,6 (11%)	0,06 (1%)
Dyke foot nourishment	1,3 (23%)	1 (18%)	3 (51%)	0,08 (0,4%)
2015				
Central tidal flat	15,6 (48%)	2,9 (19%)	1,8 (11%)	0,03 (0,2%)
Main sand nourishment	16,8 (38%)	5,8 (35%)	1,2 (7%)	0,4 (2%)
Dyke foot nourishment	8,6 (33%)	1,6 (19%)	1,9 (22%)	0,06 (1%)
2016				
Central tidal flat	13,1 (62%)	1,5 (7%)	0,9 (4%)	0,5 (2%)
Main sand nourishment	8,2 (44%)	4,2 (23%)	0,8 (4%)	2,5 (14%)
Dyke foot nourishment	16,4 (69%)	4,1 (17%)	0,4 (2%)	0,6 (2%)

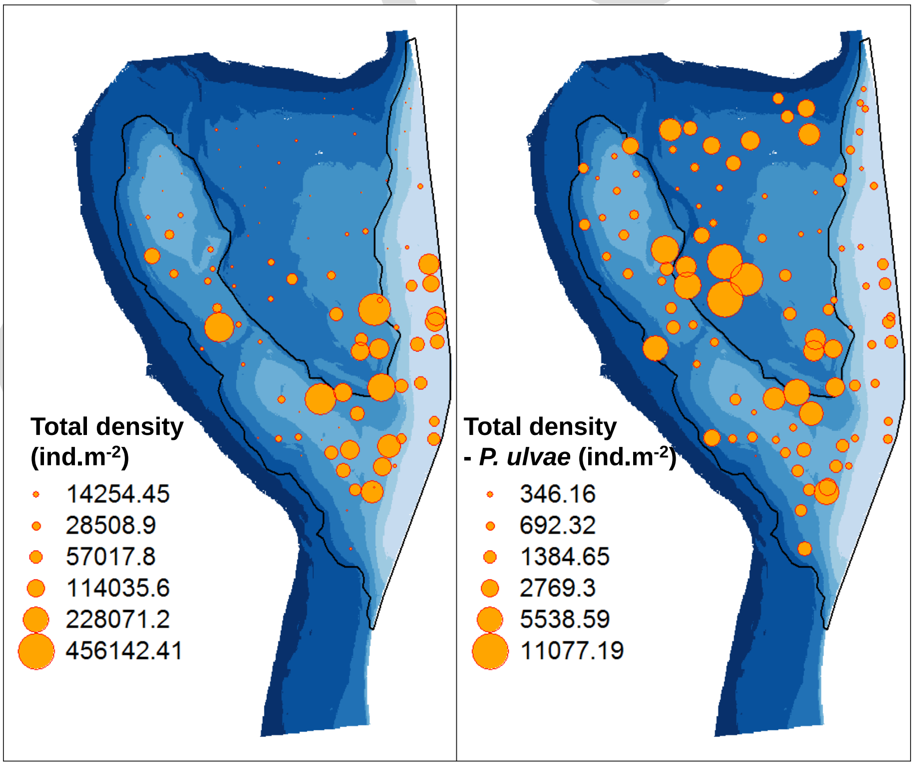


Figure 8. Total density of benthic macrofauna in 2016 (left) and total density without *Peringia ulvae* (right).

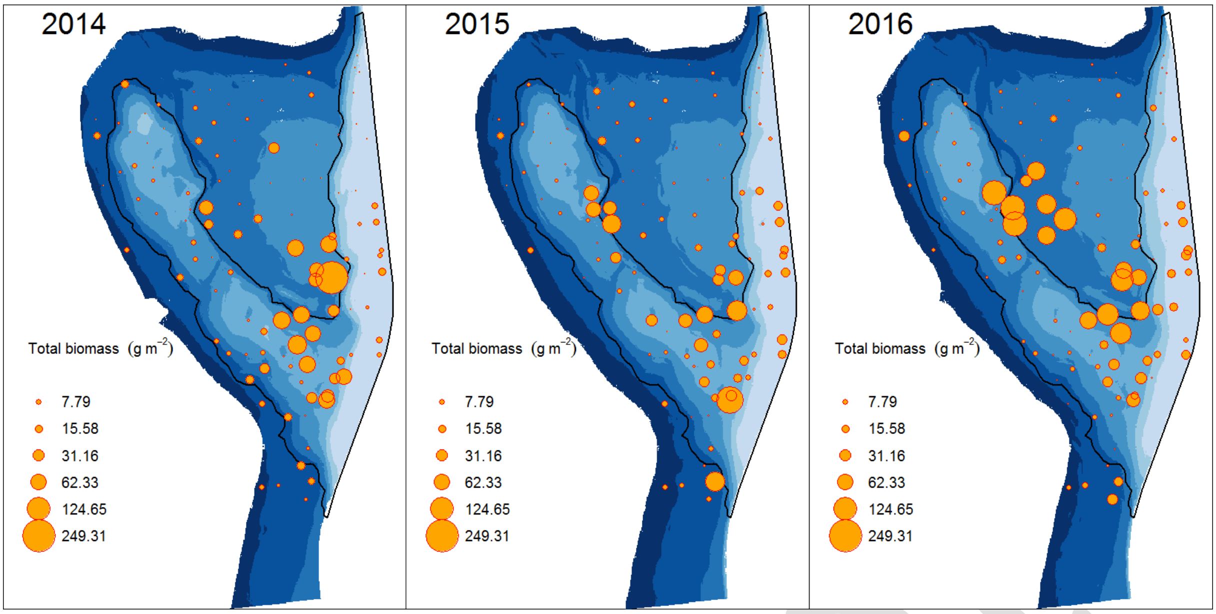


Figure 9. Distribution map of total biomass (g AFDW.m^{-2}) on the Oeterdam in 2014, 2015 and 2016.

Ecological richness showed clear clusters in each year (Figure 10). Highest ecological richness is observed in the southeast part of the Oesterdam, both on central tidal flat as on the nourished areas. Also behind the lowered area of the main sand nourishment a high ecological richness is observed. A low ecological richness is observed on the main sand nourishment at the tip, on the dyke foot nourishment in the north and at some sites on the central tidal flat.

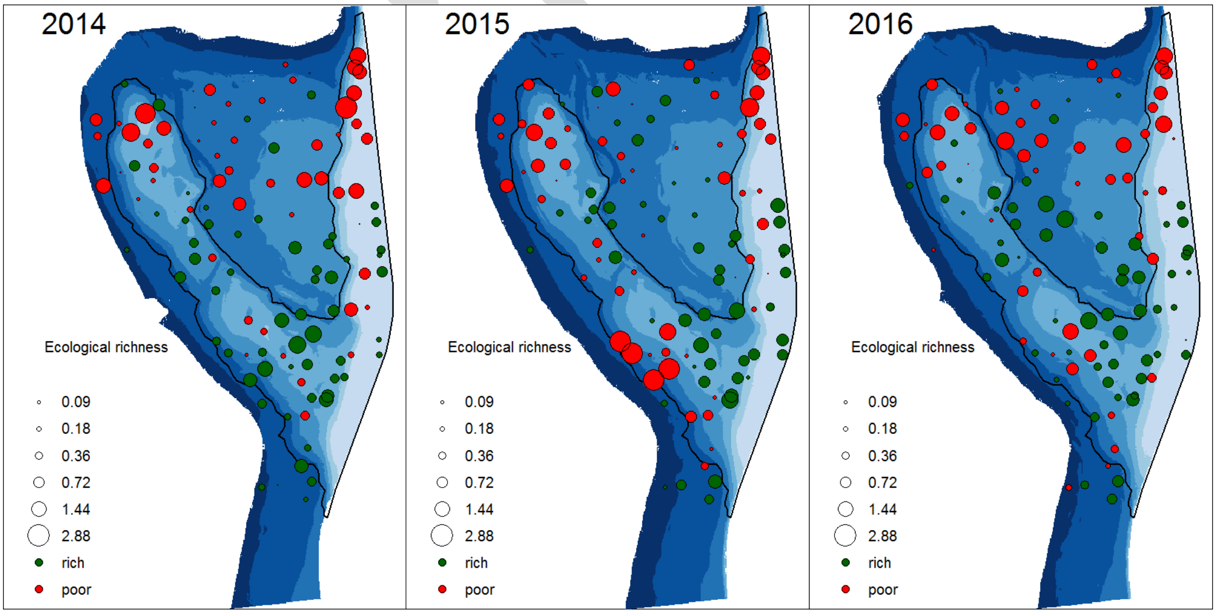


Figure 10. Distribution map of ecological richness on the Oesterdam in 2014, 2015 and 2016: green dots: positive values, red dots: negative values.

Community changes

The n-MDS based on yearly and area averaged density data showed a clear separation among areas and years (Figure 11). All three areas underwent year to year changes, but after three years the benthic communities of the central tidal flat, the dyke foot nourishment and main sand nourishment are still significantly different from each other based on an ANOSIM analysis. An n-MDS based on all stations also shows differences among areas and years (Figure 12). The benthic community of the central tidal flat seems to become more variable in 2016 compared to 2014 and 2015, as seen from the larger spreading of the sampling stations in 2016 in the n-MDS plot. Smallest dissimilarity in benthic community composition was observed for the main sand nourishment, whereas the dyke foot nourishment showed larger variability, especially in 2015.

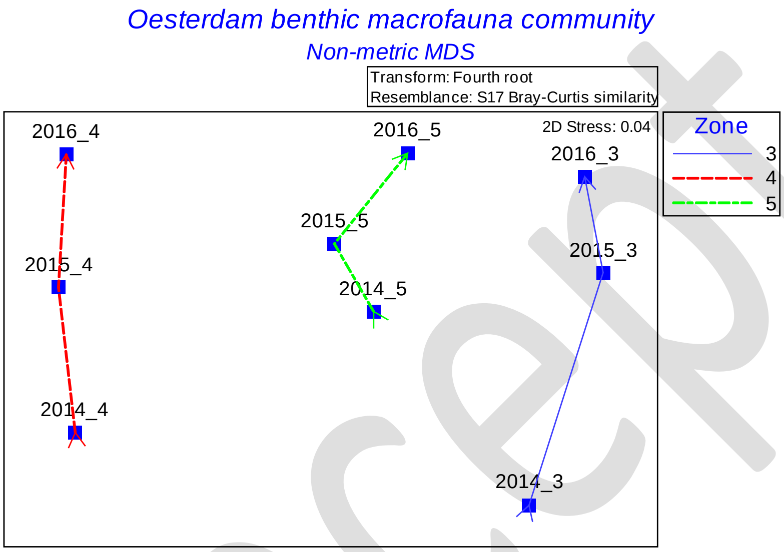


Figure 11. nMDS-plot of the changes in benthic community composition from 2014 till 2016 for the central tidal flat (zone 3), the dyke foot nourishment (zone 4), and the main sand nourishment (zone 5). The distance between the points is a measure of the dissimilarity in benthic community composition.

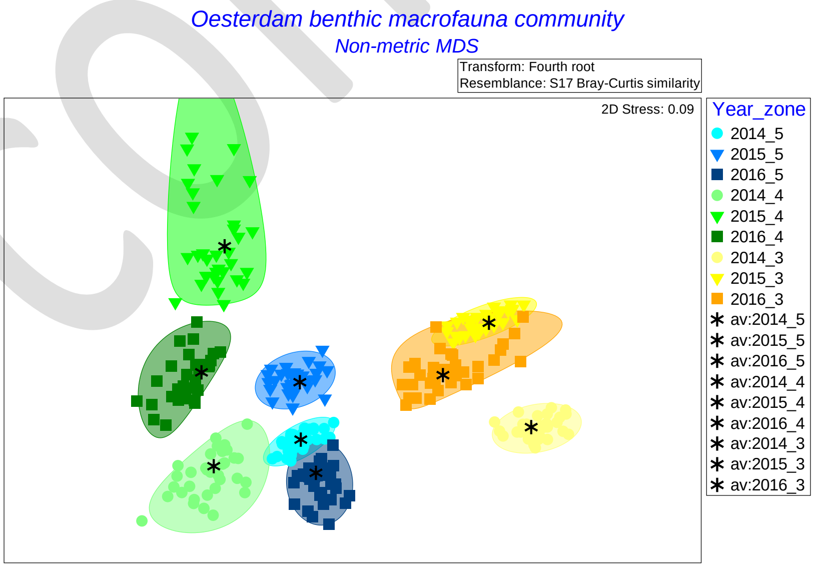
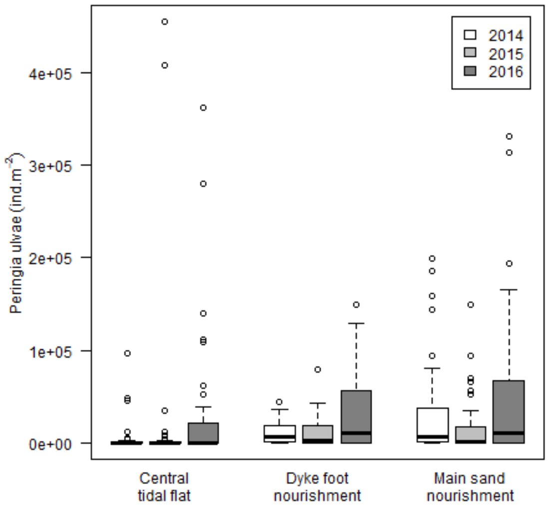


Figure 12. nMDS-plot of the changes in benthic community composition from 2014 till 2016 for the central tidal flat (zone 3), the dyke foot nourishment (zone 4), and the main sand nourishment (zone 5) based on density data. Each point represents a sampling station and the distance between the points is a measure of the dissimilarity in benthic community composition. The coloured areas denote the 95% confidence interval for each particular area in each year: yellow colours: central tidal flat, green colours: dyke foot nourishment, and blue colours: main sand nourishment. The * represents the averages for each particular area in each year.

Spatio-temporal changes of individual species

Peringia ulvae (Mollusca, Gastropoda)

The mudsnail *Peringia ulvae* (formerly known as *Hydrobia ulvae*) is a very common species on the Oesterdam. Compared to the T_0 situation this species came far more abundant since 2014. It is most common on the main sand nourishment, where also average density is highest (Figure 13, Figure 14). Locally it can reach very high densities, up to 450000 ind.m^{-2}, and on average this species dominates the community by > 90% (except for the central tidal flat in 2014 when it represents 72% of the total density). Densities are generally higher on the nourished areas, although densities seem to increase as well on the central tidal flat. In 2016 the species concentrate in the south eastern part, both on the nourished areas as on the central tidal flat. In comparison to the T_0 period (2012-2013), densities have increased significantly. Its contribution to the biomass is considerable (Table 7, Appendix 3).



Peringia ulvae	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	6326	11356	31753
2015	25872	11785	18761
2016	34060	37129	46923
Occurrence (%)			
2014	72	85	95
2015	67	57	73
2016	58	76	74

Figure 13. Left: Boxplot of Peringia *ulvae* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016. Right: Average density (ind.m-2) and occurrence (%) per year and area.

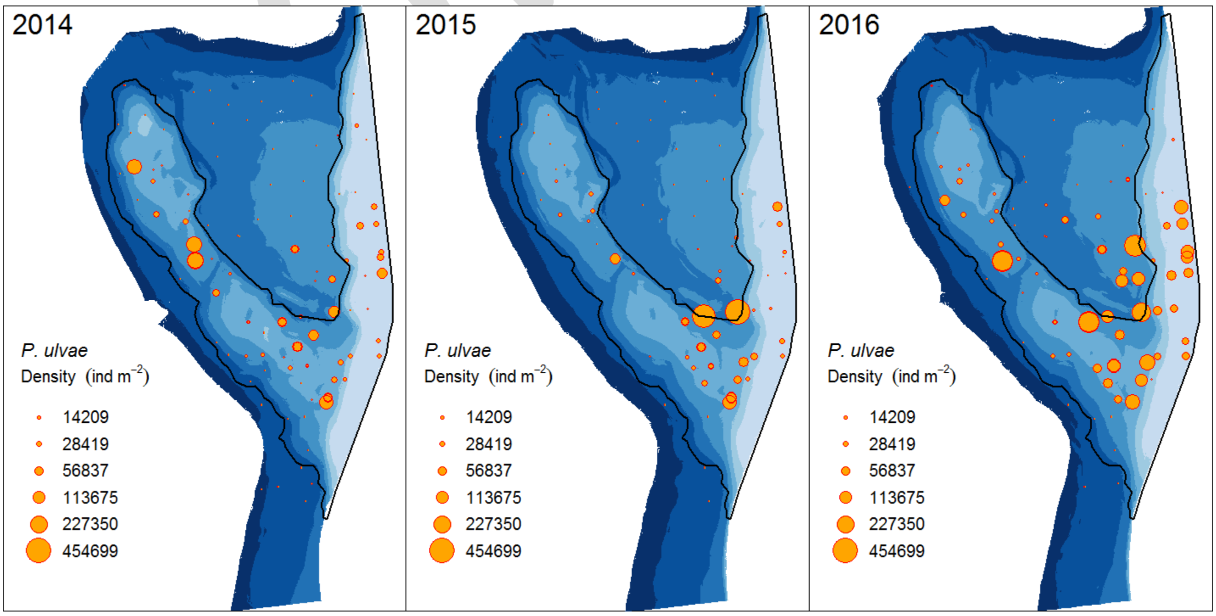
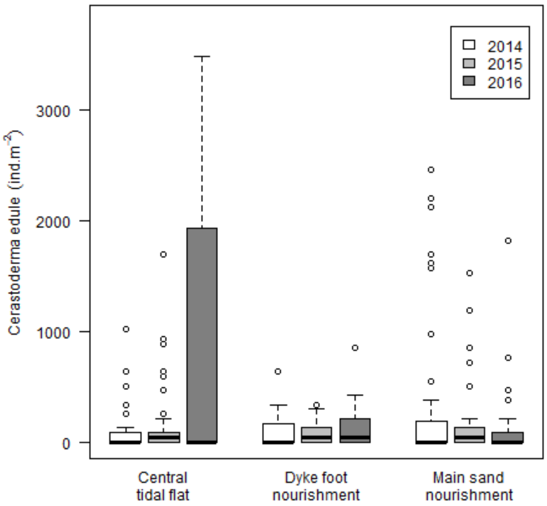


Figure 14. Distribution map of *Peringia ulvae* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Cerastoderma edule (Mollusca, Bivalvia)

The cockle *Cerastoderma edule* is an important suspension feeder in the Oosterschelde, but occurs in less high densities in the eastern part. This was reflected in the T_0 situation with low occurrence and density. After the nourishment, *C. edule* clearly colonized the nourished areas (Figure 15 and Figure 16) and succesfull spatfall was observed in each year. In 2014 this was mainly in the south eastern part on the main sand nourishment, but also on the central tidal flat successful spatfall was observed (near the nourishment). In 2015 and especially 20106 *C. edule* numbers were very high on the central tidal flat near the main sand nourishment, with somewhat lower densities on the nourishment itself (Figure 15 and Figure 16). Locally high densities of > 2000 ind.m^{-2} can be observed. *C. edule* is by far the most important species in terms of biomass (Table 7, Appendix 3).



Cerastoderma edule			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	93	117	355
2015	182	84	162
2016	694	131	250
Occurrence (%)			
2014	36	57	48
2015	67	57	63
2016	42	52	44

Figure 15. Left: Boxplot of *Cerastoderma edule* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). One outlier on the main sand nourishment in 2016 is not shown (5602 ind.m^{-2}). Right: Average density (ind.m-2) and occurrence (%) per year and area.

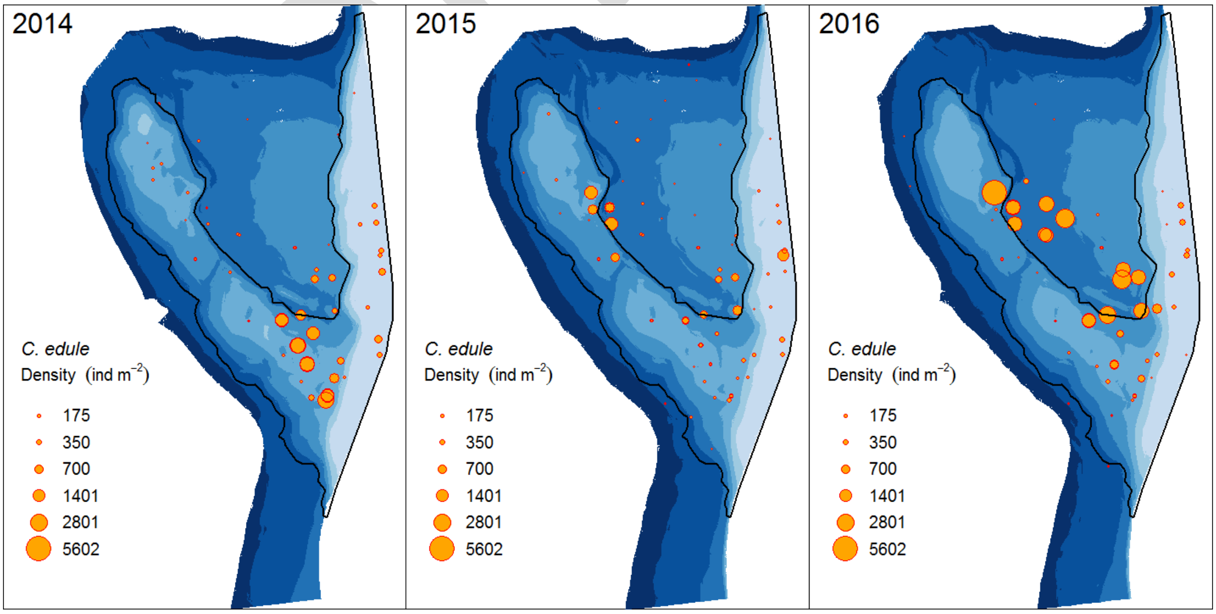
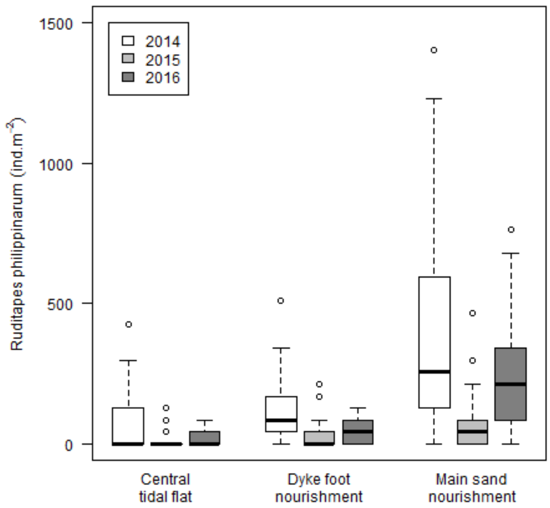


Figure 16. Distribution map of *Cerastoderma edule* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Ruditapes philippinarum (Mollusca, Bivalvia)

The Manila clam *Ruditapes philippinarum* is a non-indigenous species that is increasingly observed in the Oosterschelde. On the Oesterdam this species was rather rare in the T_0 situation, but *Ruditapes philippinarum* successfully colonized the nourished areas in 2014, especially the main sand nourishment (Figure 17 and Figure 18). In 2015 occurrence and density dropped, but showed again an increase in 2016, especially on the main sand nourishment, indicating new successful spatfall in 2016. In comparison to *Cerastoderma edule*, *Ruditapes philippinarum* is more restricted to the nourished areas. Because of the small size of the indiviuals the contribution to the biomass is still rather limited (< 8%).



Ruditapes philippinarum			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	71	212	393
2015	17	34	69
2016	16	42	237
Occurrence (%)			
2014	42	76	86
2015	19	38	61
2016	31	57	93

Figure 17. Left: Boxplot of *Ruditapes philippinarum* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). One outlier on the dyke foot nourishment in 2014 is not shown (2292 ind.m^{-2}). Right: Average density (ind.m-2) and occurrence (%) per year and area.

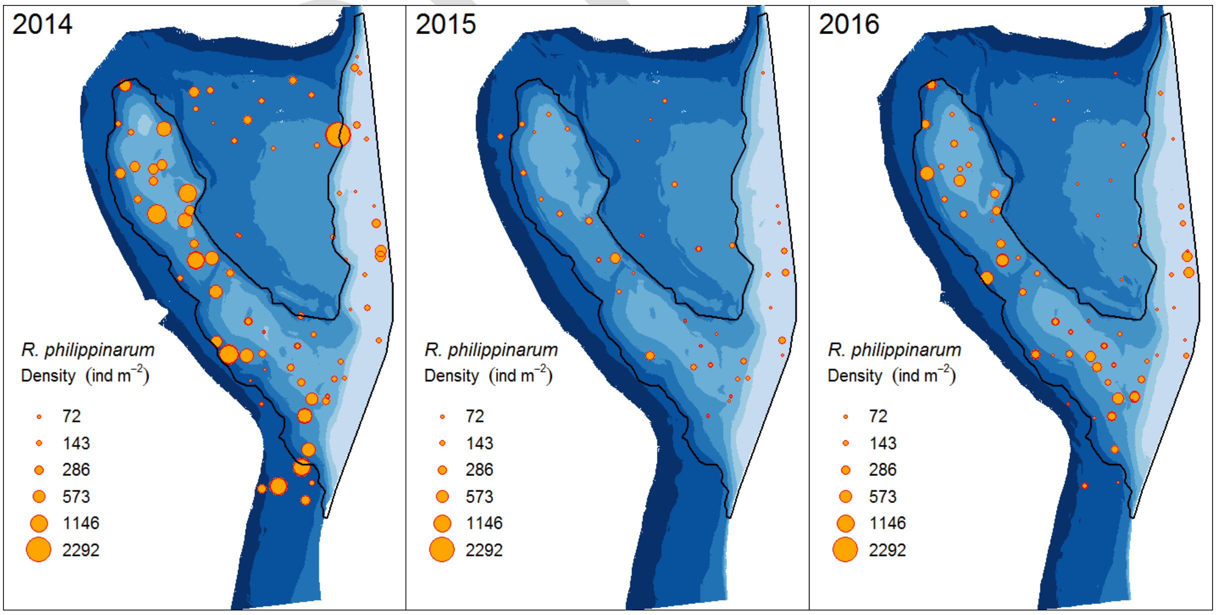
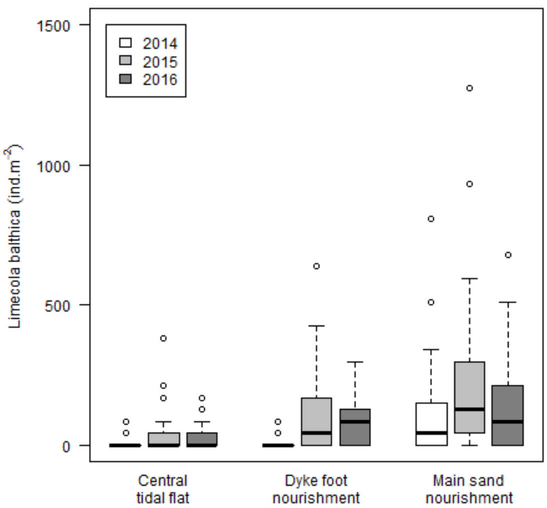


Figure 18. Distribution map of *Ruditapes philippinarum* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Limecola balthica (Mollusca, Bivalvia)

The bivalve *Limecola balthica* (formerly known as *Macoma balthica*) is a common surface deposit feeder in the Oosterschelde, but was rather rare on the Oesterdam prior to the nourishment (T_0 situation). *L. balthica* colonized the nourishment already in 2014, especially on the main sand nourishment (Figure 19 and Figure 20). From 2015 it also colonized the dyke foot nourishment, but less common and in lower densities compared to the main sand nourishment. On the central tidal flat *Limecola balthica* was less common, but also increases over the three years. Locally high densities of > 1000 ind.m^{-2} were observed. Just like *Ruditapes philippinarum*, *Limecola balthica* is more restricted to the nourished areas compared to *Cerastoderma edule*. The contribution of L. balthica to the total biomass is limited, only in 2016 it represents 14% on the main sand nourishment.



Limecola balthica	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m-2)			
2014	8	16	108
2015	35	119	204
2016	27	78	192
Occurrence (%)			
2014	17	24	67
2015	33	57	80
2016	41	67	72

Figure 19. Left: Boxplot of *Limecola balthica* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). One outlier on the main sand nourishment in 2016 is not shown (2716 ind.m^{-2}). Right: Average density (ind.m-2) and occurrence (%) per year and area.

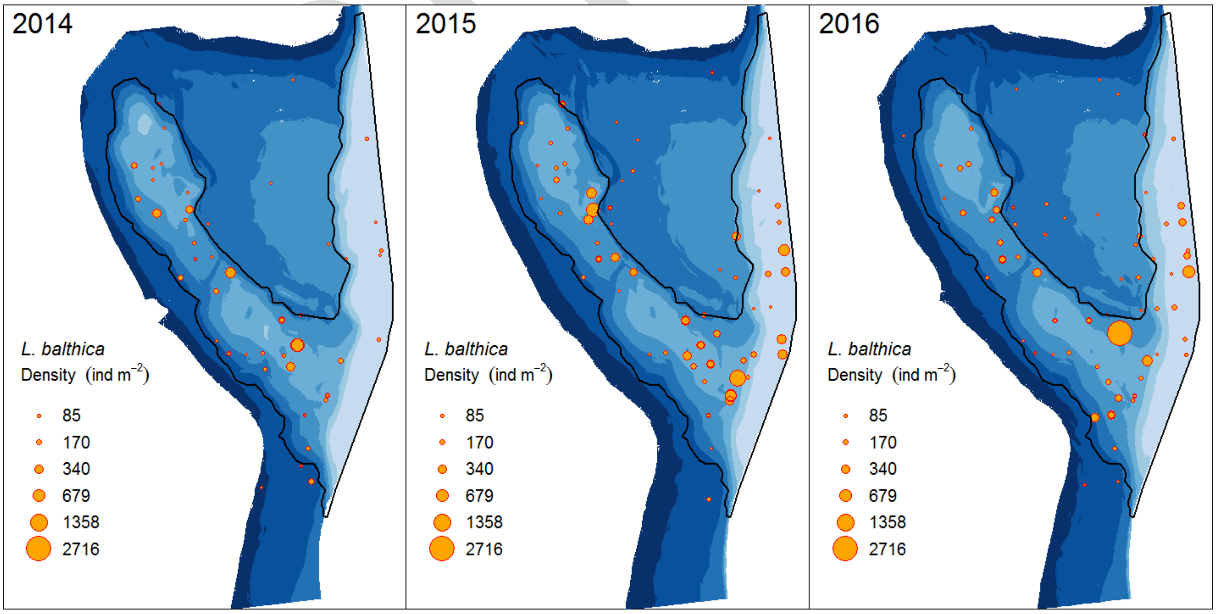


Figure 20. Distribution map of *Limecola balthica* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Arenicola marina (Annelida, Polychaeta)

The lugworm *Arenicola marina* is one of the most common polychaete species in the Oosterschelde and on the Oesterdam. The nourishment had a significant effect on the lugworm *Arenicola marina* (Figure 21, Figure 22). Juveniles (i.e. small *Arenicola* castings) colonized the dyke foot nourishment and south eastern part of the main nourishment in 2014 and mainly the dyke foot nourishment in 2015 (Figure 23). In 2016 only low numbers of juveniles were observed. Adults almost completely disappeared in the nourished areas in 2014, but gradually increased in numbers on the dyke foot nourishment and south eastern part of the main nourishment (Figure 24). On the central tidal flat an opposite trend can be observed with a gradual decrease in numbers. A. marina is the most dominant polychaete in terms of biomass, but the importance of this species decreased over the years (Table 7, Appendix 3).

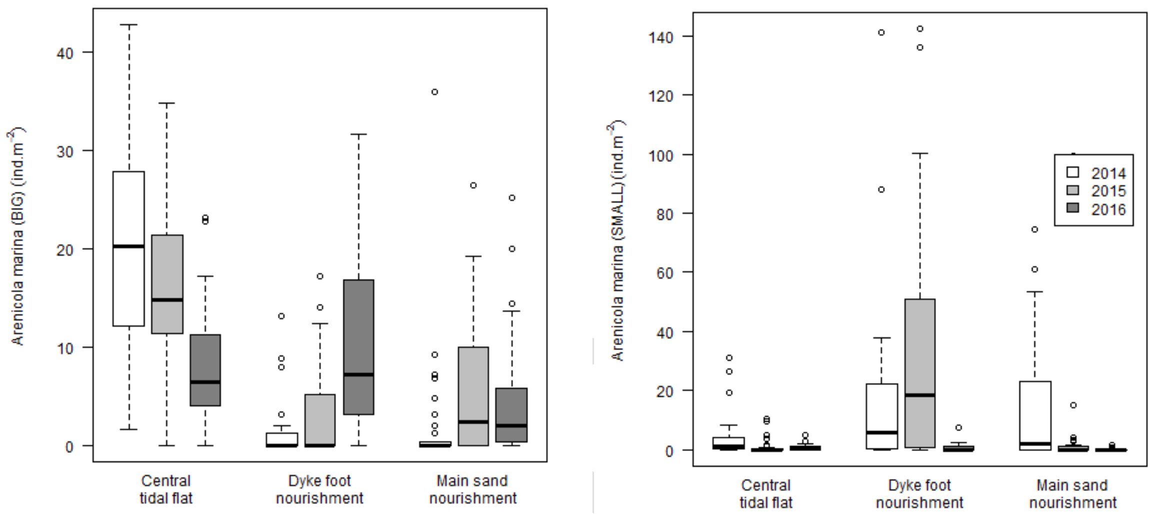


Figure 21. Boxplot of *Arenicola marina* density (number of castings.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Left: Number of large (big) *Arenicola* castings. Right: Number of small (juvenile) *Arenicola* castings.

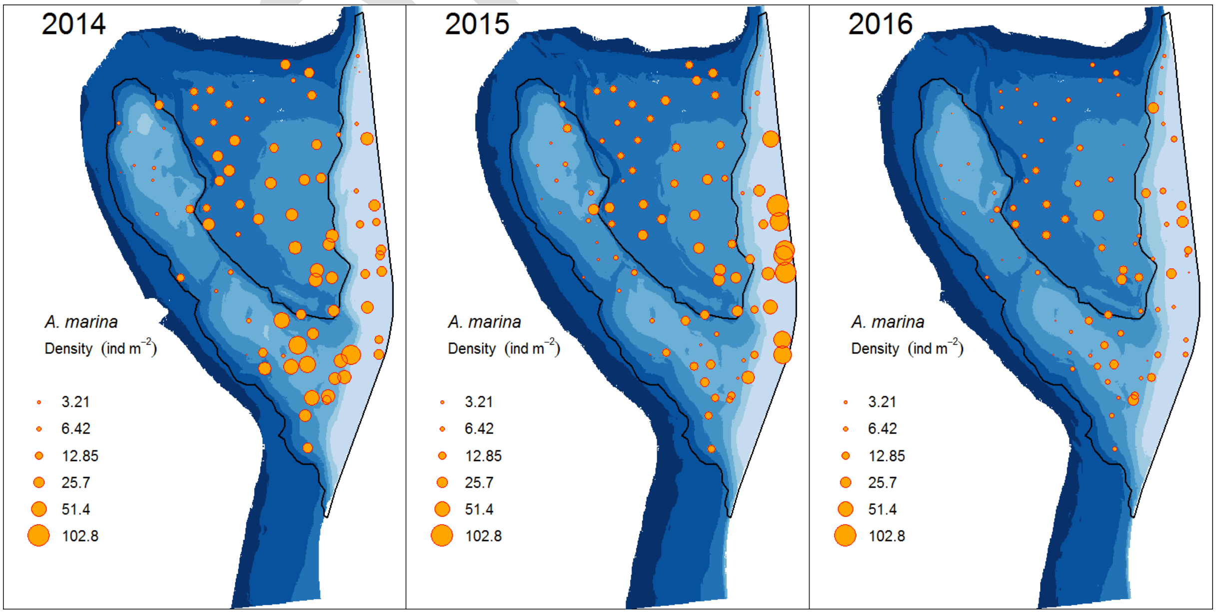


Figure 22. Distribution map of *Arenicola marina* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

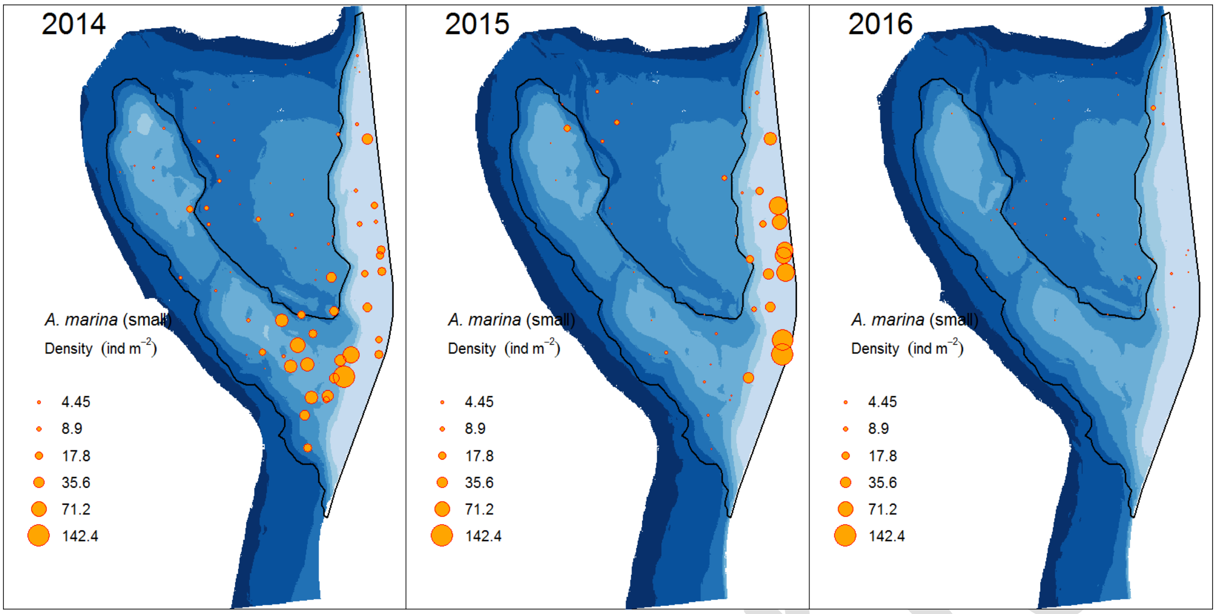


Figure 23. Distribution map of small (juvenile) *Arenicola marina* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

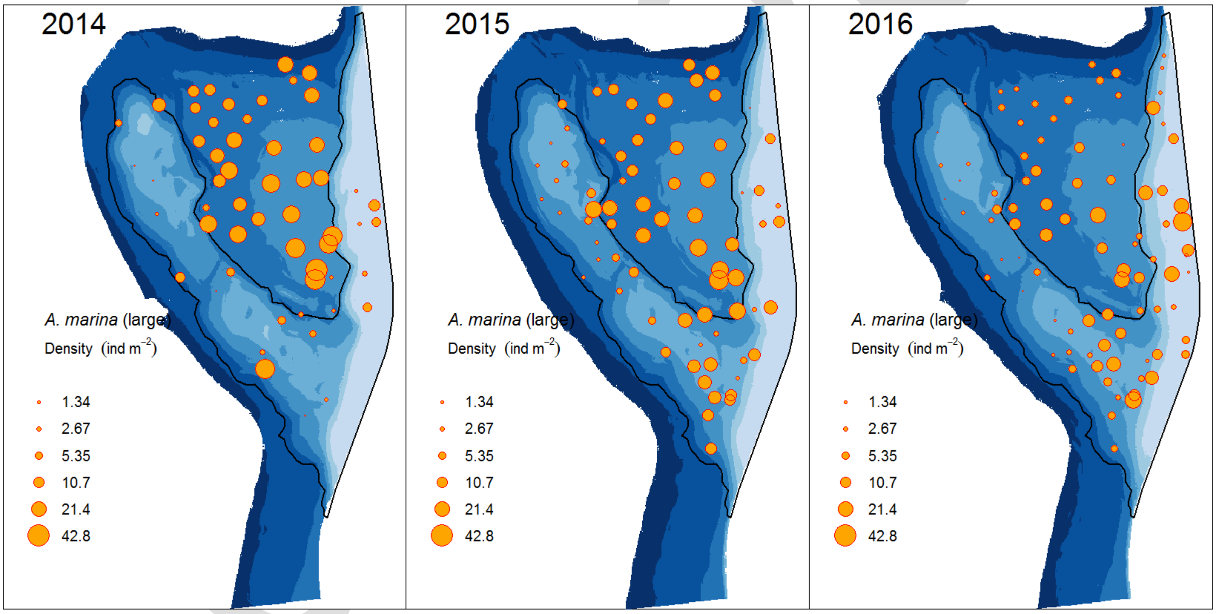
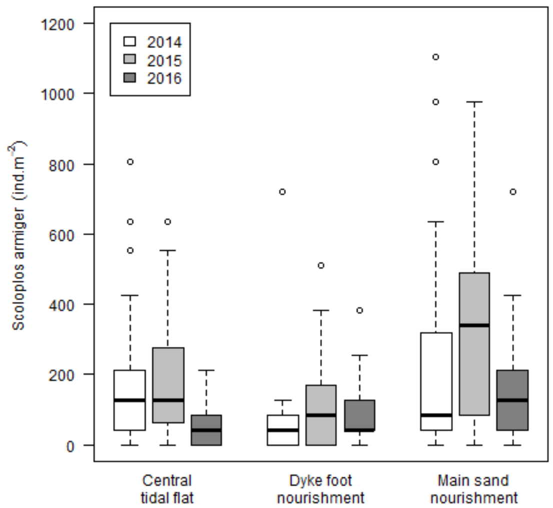


Figure 24. Distribution map of large *Arenicola marina* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Scoloplos armiger (Annelida, Polychaeta)

The bristle worm *Scoloplos armiger* is one of the most commonly observed species in the Oosterschelde. The species was very common and abundant in the T_0 situation, and it rapidly colonized the nourished areas in 2014 and is now a very common species on the Oesterdam in all areas (Figure 25 and Figure 26). Densities of *Scoloplos armiger* varied among years and areas and were on average lowest in 2016. In terms of biomass, *S. armiger* is the second most important polychaete; it contributes between 1 and 7% to the total biomass, depending on the area and the year (Appendix 3 for spatial distribution map).



Scoloplos armiger			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	286	70	215
2015	183	123	319
2016	44	81	140
Occurrence (%)			
2014	89	62	86
2015	86	71	95
2016	67	76	91

Figure 25. Left: Boxplot of *Scoloplos armiger* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). One outlier on the central tidal flat in 2014 is not shown (4541 ind.m^{-2}). Right: Average density (ind.m-2) and occurrence (%) per year and area.

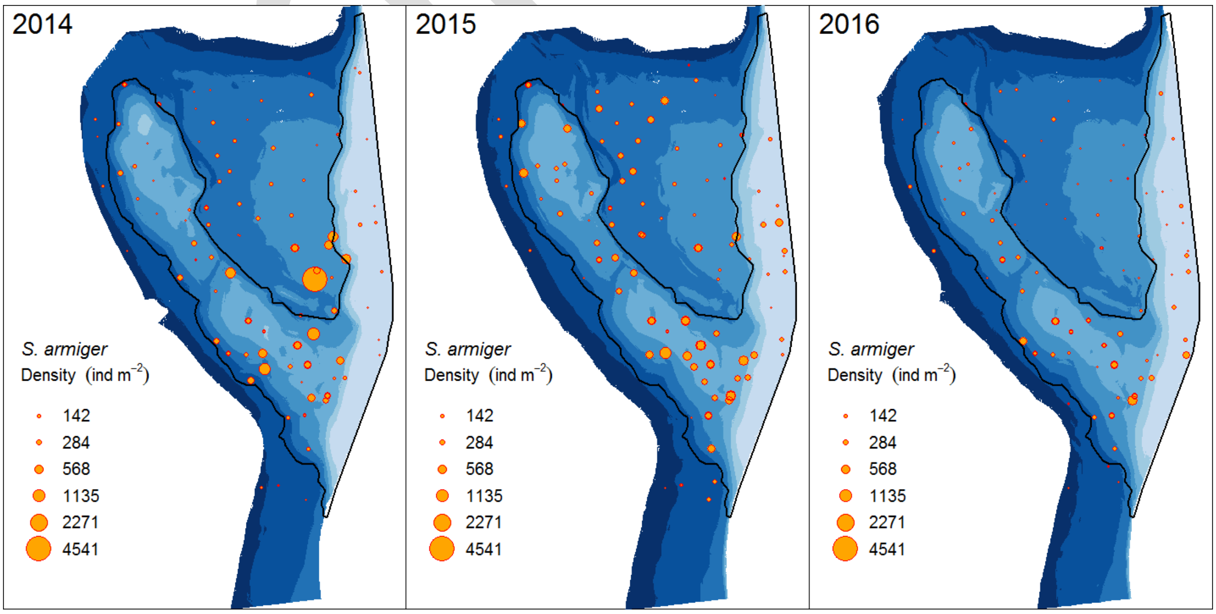
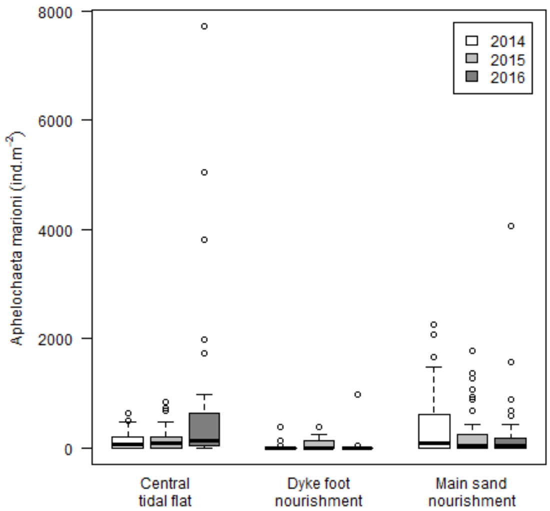


Figure 26. Distribution map of *Scoloplos armiger* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Aphelochaeta marioni (Annelida, Polychaeta)

Aphelochaeta marioni is a type of relatively small bristle worm that is common in the Oosterschelde. Like *Scoloplos armiger* is was already relatively common in the T_0 situation and *Aphelochaeta marioni* successfully colonized the nourished areas, especially the main sand nourishment and to a lesser extent the dyke foot nourishment (Figure 27 and Figure 28). Densities varies over the years, and in 2016 also an area on the central tidal flat showed high densities of *Aphelochaeta marioni*.



Aphelochaeta marioni			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	123	30	434
2015	163	65	261
2016	754	55	256
Occurrence (%)			
2014	67	24	65
2015	72	33	60
2016	81	24	60

Figure 27. Left: Boxplot of *Aphelochaeta marioni* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Right: Average density (ind.m-2) and occurrence (%) per year and area.

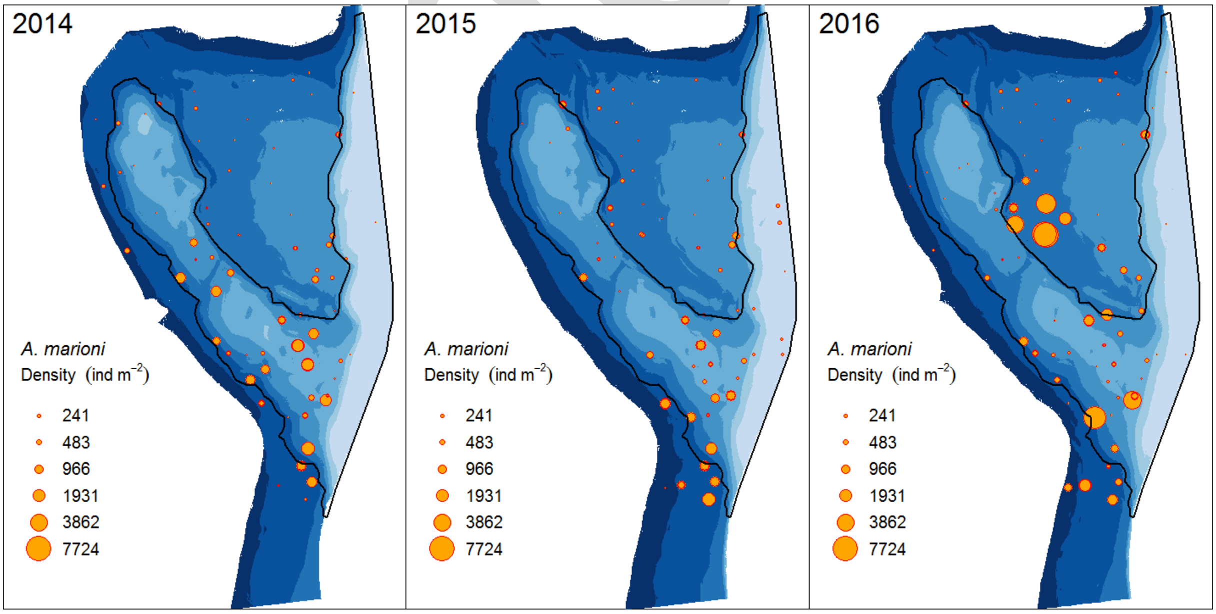
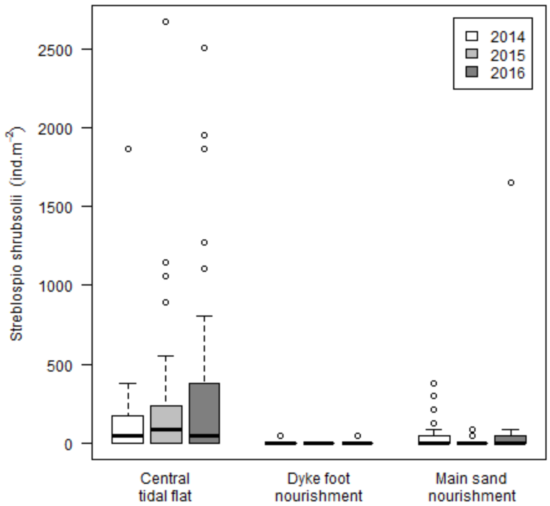


Figure 28. Distribution map of *Aphelochaeta marioni* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Streblospio shrubsolii (Annelida, Polychaeta)

Streblospio shrubsolii is a small bristle worm belonging to the Spionidae, a family with several common species in the Oosterschelde. Other known species in this family are *Pygospio elegans* and *Polydora cornuta*. *Pygospio elegans* colonized the main sand nourishment in 2014, but subsequently decreased in numbers. Contrary, *Streblospio shrubsolii* (and also *Polydora cornuta*) did not colonize the nourished areas yet (Figure 29 and Figure 30). Especially on the dyke foot nourishment it is hardly seen.



Streblospio shrubsolii			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	147	2	35
2015	258	0	4
2016	386	2	52
Occurrence (%)			
2014	64	5	28
2015	69	0	7
2016	67	5	28

Figure 29. Left: Boxplot of *Streblospio shrubsolii* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Right: Average density (ind.m-2) and occurrence (%) per year and area.

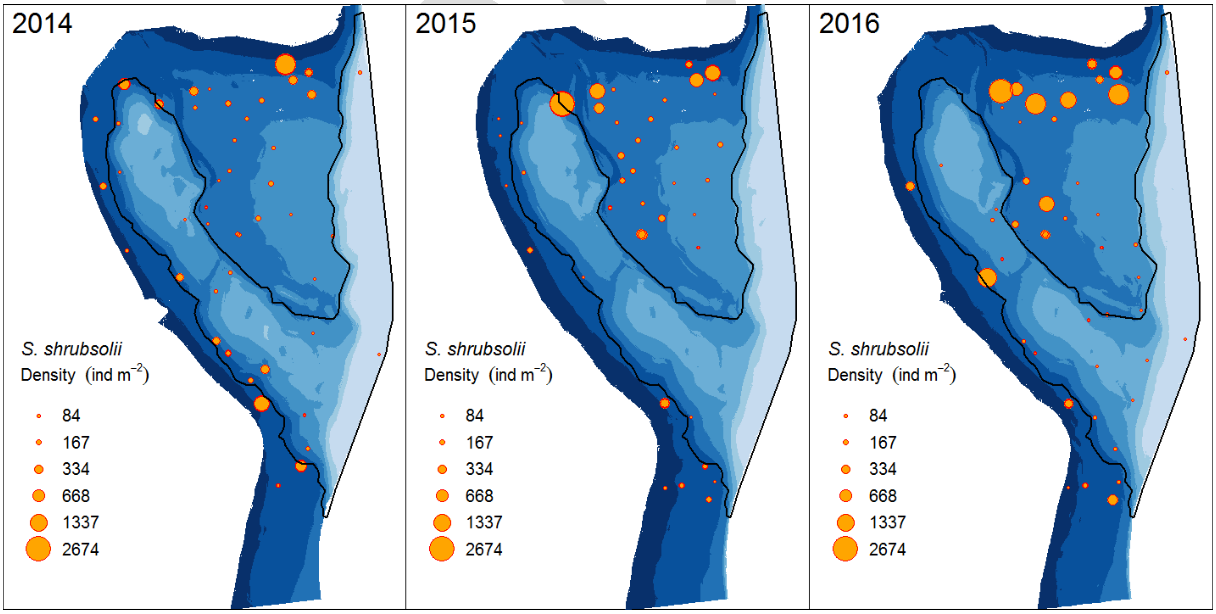
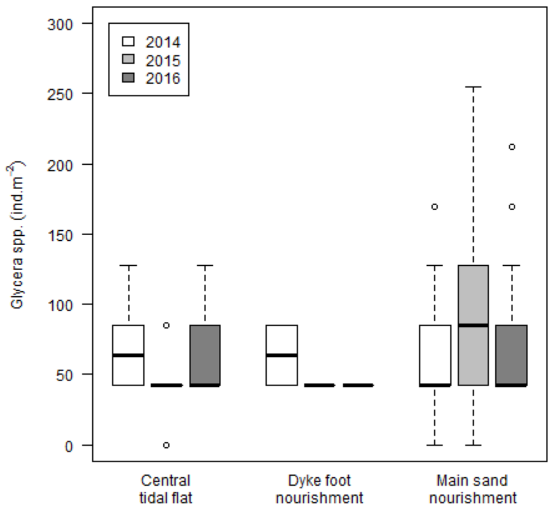


Figure 30. Distribution map of *Streblospio shrubsolii* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Glycera spp. (Annelida, Polychaeta)

The bloodworm *Glycera spp.* is a relatively common species on the Oesterdam, and it rapidly colonized the main sand nourishment. In 2015 and 2016 occurrence and density further increased on the main sand nourishment, whereas on the dyke foot nourishment the species occurred less and only in very low densities (Figure 31 and Figure 32).



Glycera spp.			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	51	6	31
2015	22	6	45
2016	25	8	54
Occurrence (%)			
2014	72	10	47
2015	50	14	54
2016	44	19	81

Figure 31. Left: Boxplot of *Glycera spp.* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Right: Average density (ind.m-2) and occurrence (%) per year and area.

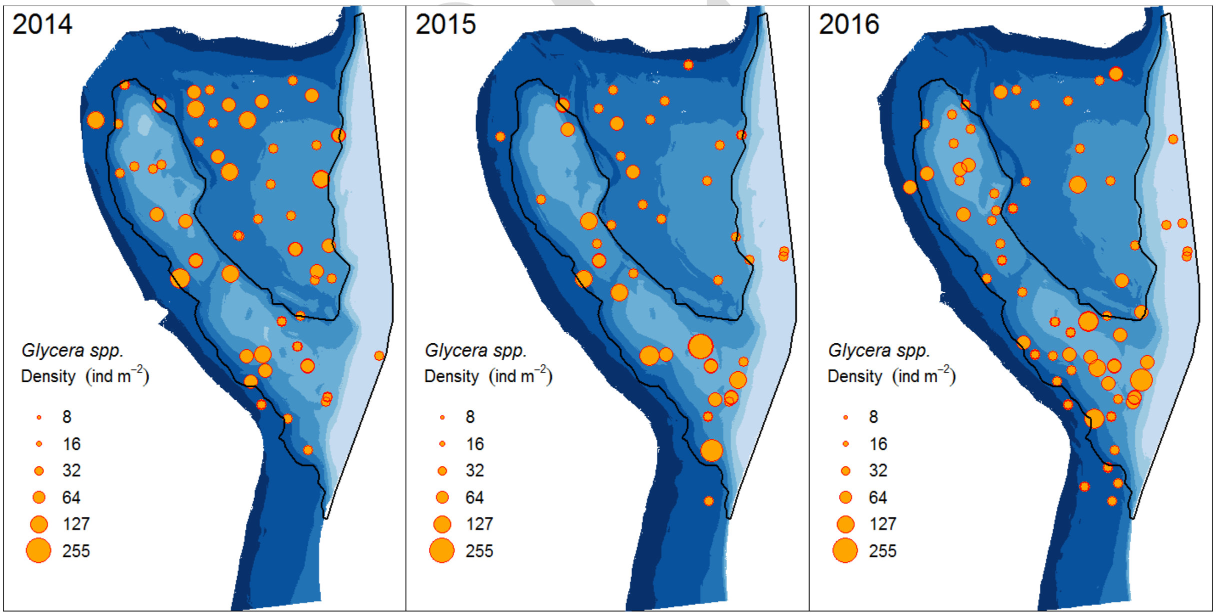
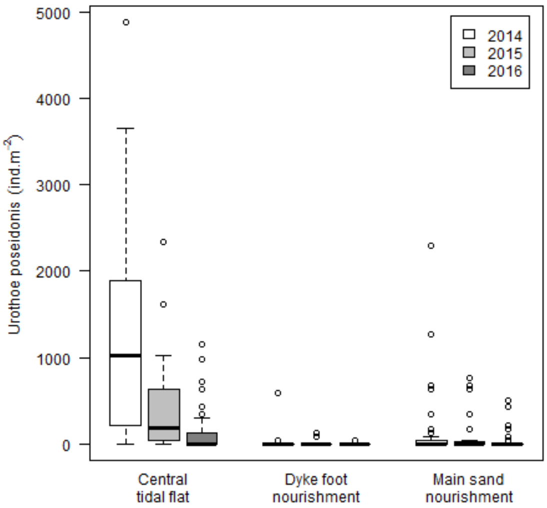


Figure 32. Distribution map of *Glycera spp.* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Urothoe poseidonis (Arthropoda, Crustacea)

Urothoe poseidonis is a small amphipod crustacean common in the Oosterschelde. It was very common in the T_0 situation, and also in 2014 this species was very common and abundant on the central tidal flat, but did not colonize the nourished areas in large numbers (Figure 33 and Figure 34). In 2015 and especially in 2016 occurrence and density decreased in all areas.



Urothoe poseidonis			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	1285	32	138
2015	372	16	66
2016	144	2	34
Occurrence (%)			
2014	97	14	30
2015	83	14	27
2016	39	5	14

Figure 33. Left: Boxplot of Urothoe *poseidonis* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Right: Average density (ind.m-2) and occurrence (%) per year and area.

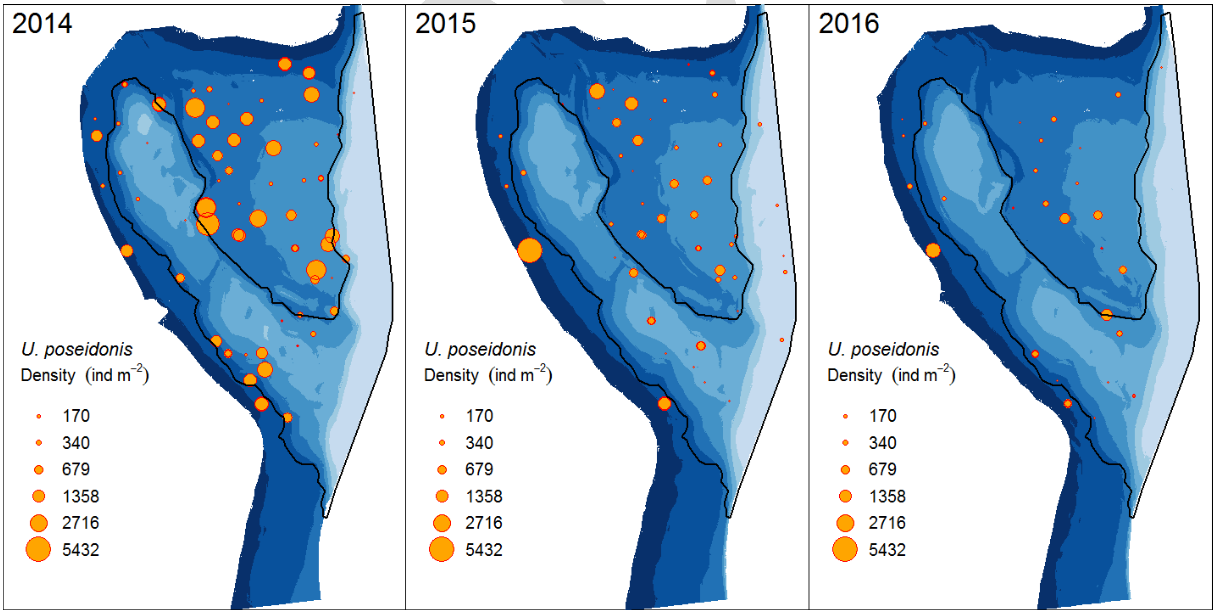
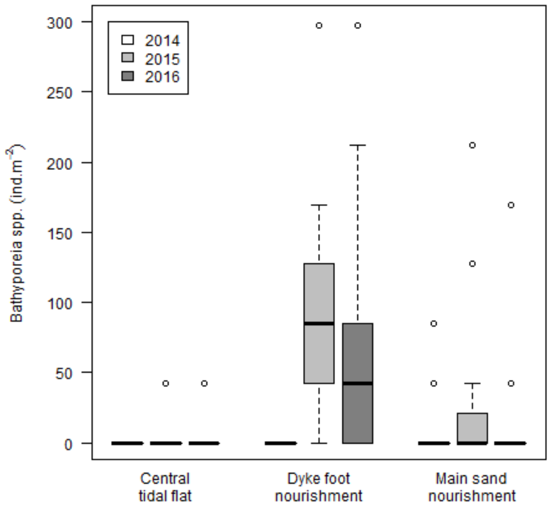


Figure 34. Distribution map of *Urothoe poseidonis* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Bathyporeia spp. (Arthropoda, Crustacea)

Bathyporeia spp. are, just like *Urothoe poseidonis*, small amphipod crustaceans. But unlike *Urothoe poseidonis*, *Bathyporeia spp.* was absent in the T_0 situation, hardly present in 2014, after which it colonized the area in 2015 and 2016, especially on the dyke foot nourishment (Figure 35 and Figure 36). On the central tidal flat this species was hardly present.



Bahtyporeia spp.			
	Central tidal flat	Dyke foot nourishment	Main sand nourishment
Density (ind.m^{-2})			
2014	0	0	3
2015	1	103	19
2016	4	73	7
Occurrence (%)			
2014	0	0	5
2015	3	85	27
2016	8	67	9

Figure 35. Left: Boxplot of *Bathyporeia spp.* density (ind.m^{-2}) showing differences among areas (central tidal flat, dyke foot nourishment, main sand nourishment) and years (2014, 2015, 2016). Right: Average density (ind.m-2) and occurrence (%) per year and area.

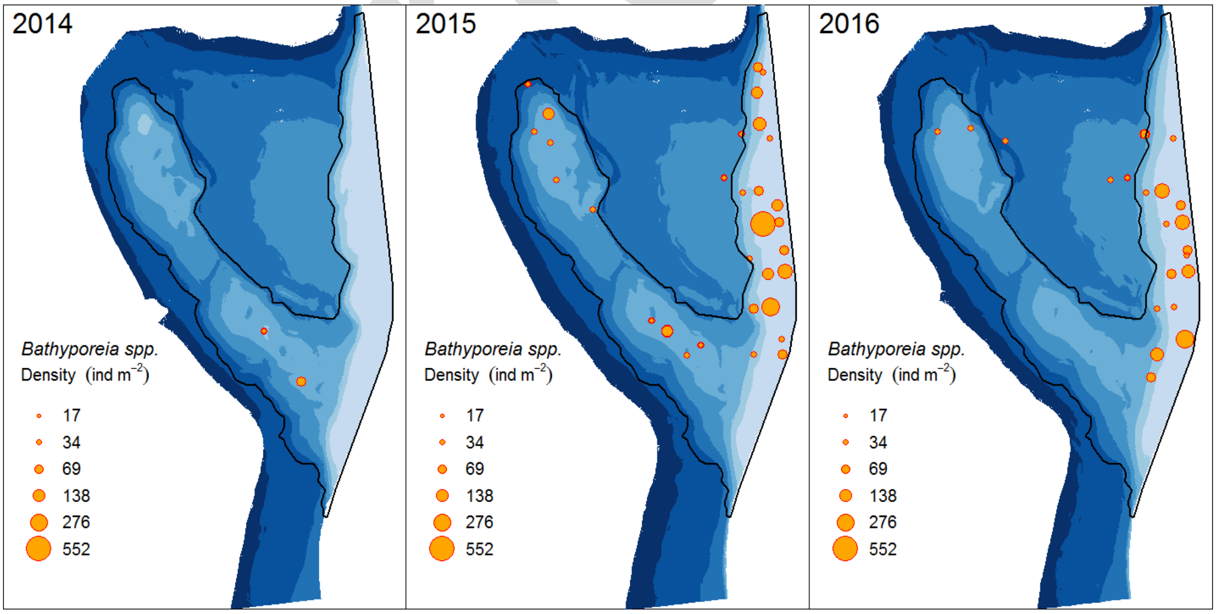


Figure 36. Distribution map of *Bathyporeia spp.* density (ind.m^{-2}) on the Oesterdam in 2014, 2015, and 2016. The original contour of the nourishment is shown with the black line.

Changes over time in benthic macrofauna based on the qualitative monitoring approach

The area-wide inventory of some benthic species showed in general good correspondence with the benthic macrofauna sampled in more detail at the 114 stations. The main findings are discussed below and in Appendix 4 maps of all taxa observed are shown.

The lugworm *Arenicola marina* is the most common species observed in the qualitative monitoring. The lugworm was observed at almost every sampling point in August 2013, prior to the nourishment (Figure 37). In April 2014, some juvenile and medium-sized lugworms were observed on the main sand nourishment, whereas no lugworms were observed on the dyke foot nourishment, due to the re-profiling of this nourishment section in March 2014. In September 2014 and 2015 juveniles are abundant on the nourishment, especially on the dyke foot nourishment. In September 2016 the lugworm seems to become less abundant, both on the nourished areas as on the central tidal flat.

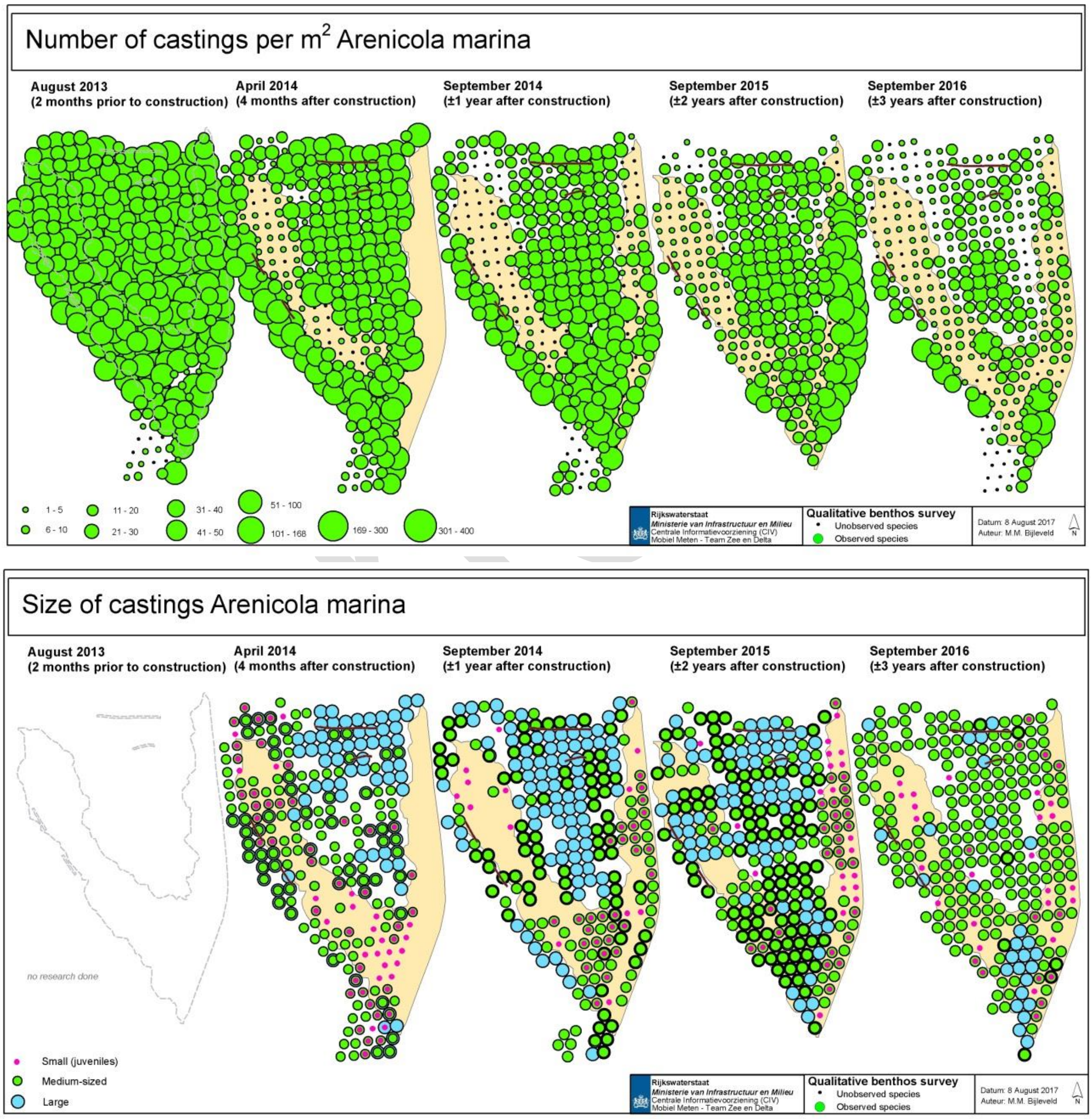


Figure 37. Distribution of the lugworm *Arenicola marina* on the Oesterdam. Top: ind.m^{-2}. Bottom: Size of the castings: purple = small (juveniles), green = medium-sized, blue = large.

The mudsnail *Peringia ulvae* was not observed during the qualitative monitoring in August 2013, and at only a few stations in April 2014 (Figure 38). In the T_0 situation, based on the detailed benthic samples, *Peringia ulvae* was observed more frequently (Table 5), but most likely the small size of *Peringia ulvae*, together with low densities at that time, might explain the low occurrence based on the qualitative method. From September 2014 till September 2016, *Peringia ulvae* is increasingly observed, especially on the nourished areas, but also on the central tidal flat in 2016. As densities were high in this period (Figure 13), *Peringia ulvae* was most likely more easily detected during the qualitative monitoring.

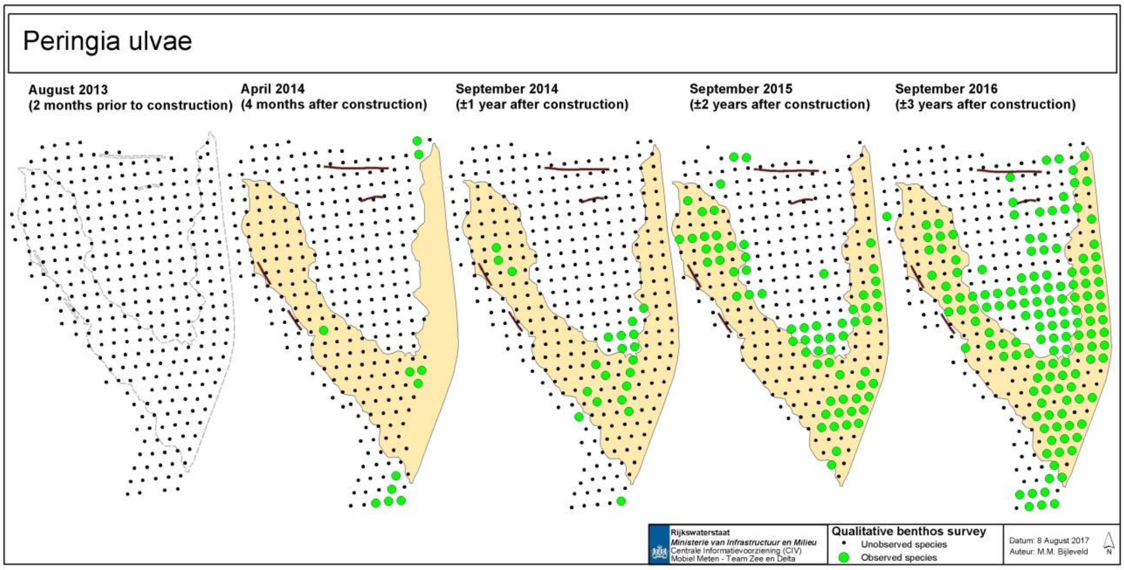


Figure 38. Distribution of *Peringia ulvae* on the Oesterdam. Green dots = species present.

The most common bivalve based on the qualitative monitoring is the cockle *Cerastoderma edule*. In August 2013, prior to the nourishment, the cockle was commonly observed on the central tidal flat, although in low densities (Figure 39). In April 2014, as expected, no cockles were observed on the nourished areas, but in September 2014 successful spatfall was observed on the nourishment and adjacent parts of the central tidal flat (Figure 39), as also shown with the detailed benthic sampling (Figure 16). In September 2015 and in 2016 also successful spatfall is observed, especially on the central tidal flat, but also on the nourished areas, generally in line with the detailed benthic sampling. The qualitative monitoring showed that *Ruditapes philippinarum* was not very common in August 2013 and April 2014, but also in September 2014 the species was still hardly observed (Figure 39). This in contrast to the detailed benthic sampling, which showed frequent occurrences and relatively high densities on the nourished areas, especially the main sand nourishment (Figure 18). As it mainly were very small individuals that were observed in the samples, most likely specimens were too small (i.e. spatfall) to be detected by the qualitative method. In September 2015 and 2016 *Ruditapes philippinarum* is increasingly observed with the qualitative method, especially on the nourished areas, although some differences in spatial distribution are still being observed between the qualitative method and the detailed benthic sampling, probably also due to the fact that very small specimens are missed by the qualitative method.

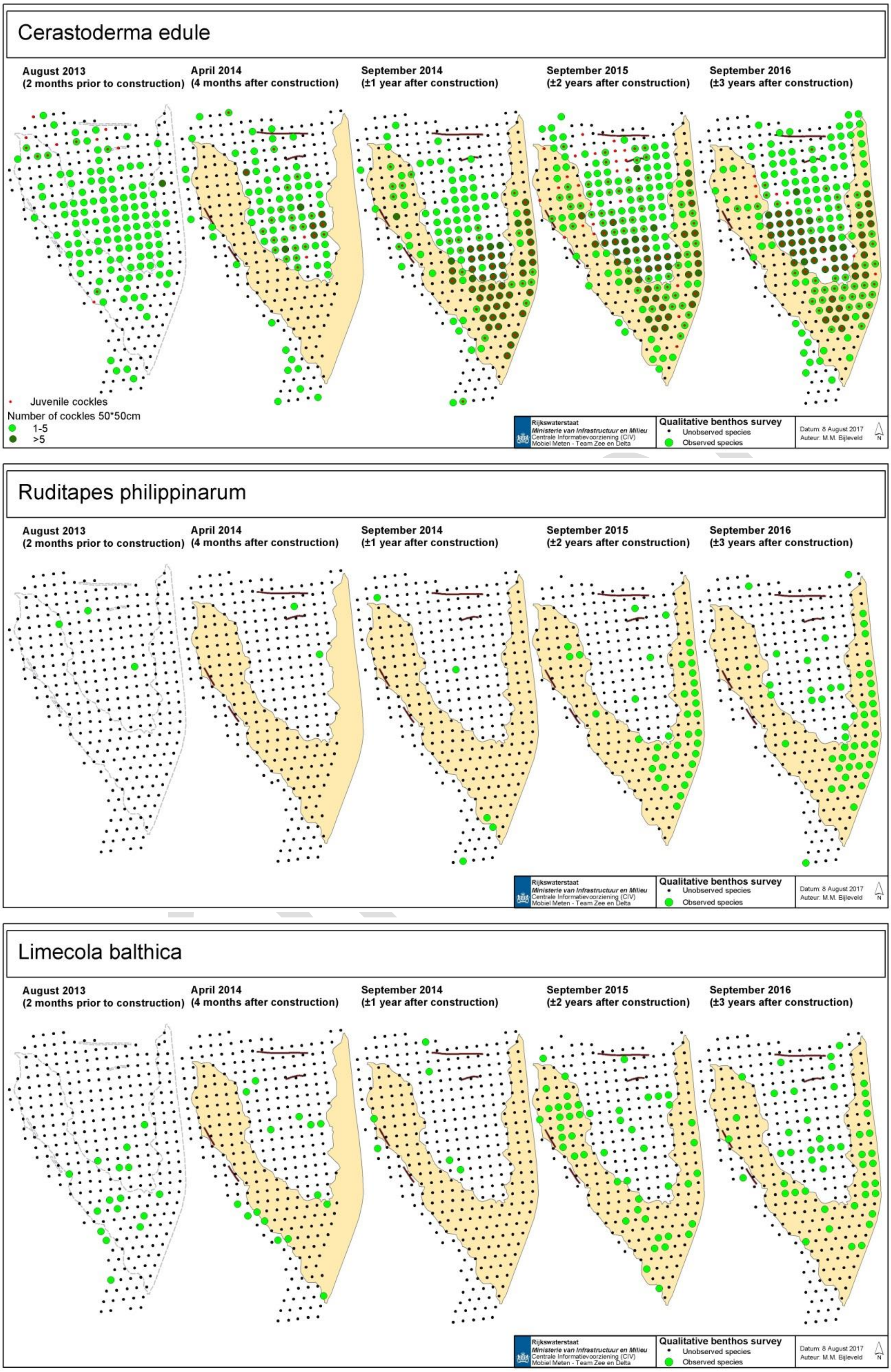


Figure 39. Distribution of *Cerastoderma edule* (top), *Limecola* (*Macoma*) *balthica* (middle) and *Ruditapes* (*Venerupis*) *philippinarum* (bottom) on the Oesterdam. For *Cerastoderma edule* a difference is made between a few ('weinig') and many ('veel') individuals, and if spatfall (juveniles) were present. For the other two species: green dots = species present.

The qualitative monitoring confirms that *Limecola balthica* was a rather rare species on the Oesterdam prior to the nourishment. Also in September 2014 it was still very rare (Figure 39), although based on the detailed benthic sampling the species was observed in 67% of the sampling station on the main sand nourishment and 24% of the sampling stations on the dyke foot nourishment. Probably specimens were too small (i.e. spatfall) to be detected by the qualitative method. In September 2015 and 2016 *Limecola balthica* was observed more frequently on the nourished areas, in line with the detailed benthic sampling (Figure 20).

The amphipod *Urothoe poseidonis* was the most common crustacean in the qualitative monitoring Figure 40), just like in the detailed monitoring on the 114 sampling stations (Figure 34). Similar to the detailed monitoring, *Urothoe poseidonis* did not colonize the nourished areas, and over time occurrence decreased in all areas, with in September 2016 hardely any observations left. The appearance of *Bathyporeia spp.* on the dyke foot nourishment in 2015 and 2016, as noticed by the detailed monitoring, was not observed with the qualitative monitoring.

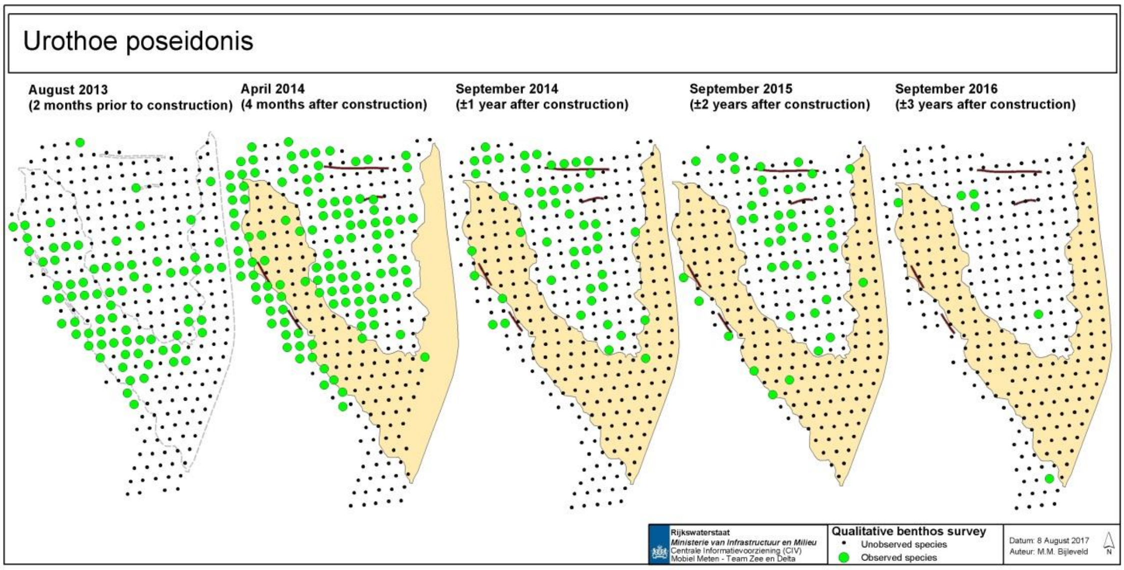


Figure 40. Distribution of the amphipod *Urothoe poseidonis* on the Oesterdam. Green = species present.

For other species the qualitative monitoring showed that the polychaetes *Glycera spp.*, *Nephtys spp.*, *Pygospio elegans* and *Scoloplos armiger* are frequently observed on the Oesterdam (see Appendix 4). The distribution of *Glycera spp.*, *Nephtys spp.* and *Scoloplos armiger* seems largely in line with the detailed benthic sampling. Pygospio elegans is much less frequently observed with the detailed benthic sampling, but here most likely determination plays a role. What is called *Pygospio elegans* in the field with the qualitative monitoring most likely must be seen as a more broader group of Spionidae species, which also contains for instance *Polydora cornuta* and *Streblospio shrubsolii*. Species like *Nereis spp.* and *Notomastus latericeus* are typically restricted to the most southern part of the Oesterdam, south of nourishment, were the sediment becomes more muddy. This area was left out from the analysis with the detailed benthic sampling. The bivalves *Ensis spp.* and *Scrobicularia plana* were not very common on the Oesterdam, and *Mya arenaria* seems to become less common as well. *Corophium spp*. are very rare on the Oesterdam, and the distribution of *Urothoe poseidonis* largely reflects the observations from the detailed benthic sampling. It is typically restricted to the central tidal flat, but at the same time it also became less common over the years. Due to the decrease in density as well in 2016, this species might be overlooked more with the qualitative monitoring.

Spatial heterogeneity along transects on the nourishment

The transects confirmed the general trends observed in the change in elevation, with the top of the main sand nourishment eroding over time (Figure 41). Also the exposed side of the nourishment showed erosion on most locations, only the lowest locations showed accretion, as sand was deposited here from the higher parts of the nourishment. At the sheltered side of the nourishment the change in elevation was more diverse; at C-C* and D-D* most locations showed accretion (Figure 41). The median grain size in general showed an increase on most sites along the transects, although some locations showed a decrease, for instance at the sheltered side along transect A-A* (Figure 42).

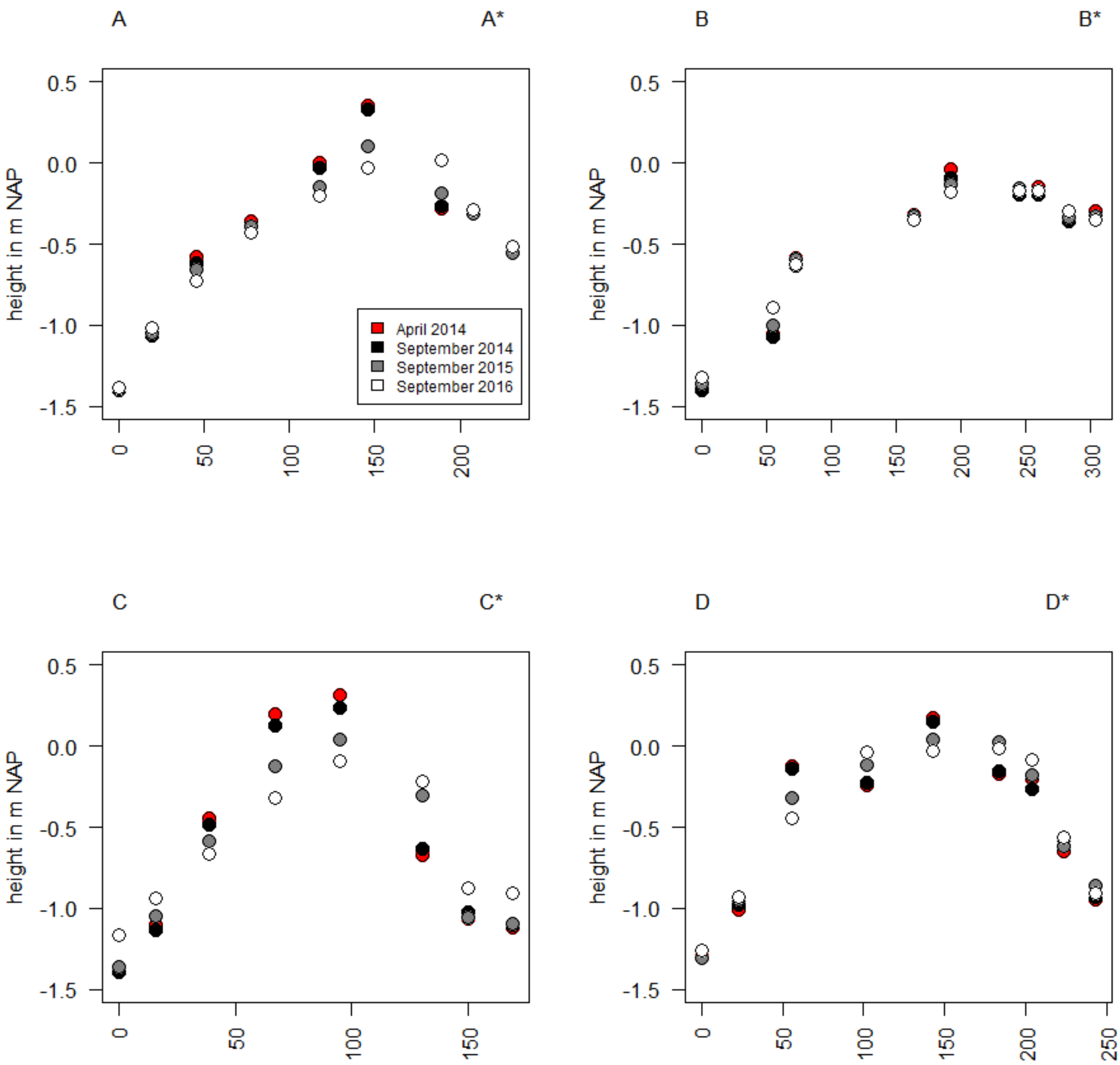


Figure 41. Elevation change along four transects on the main sand nourishment. See Figure 2 for the position of the transects.

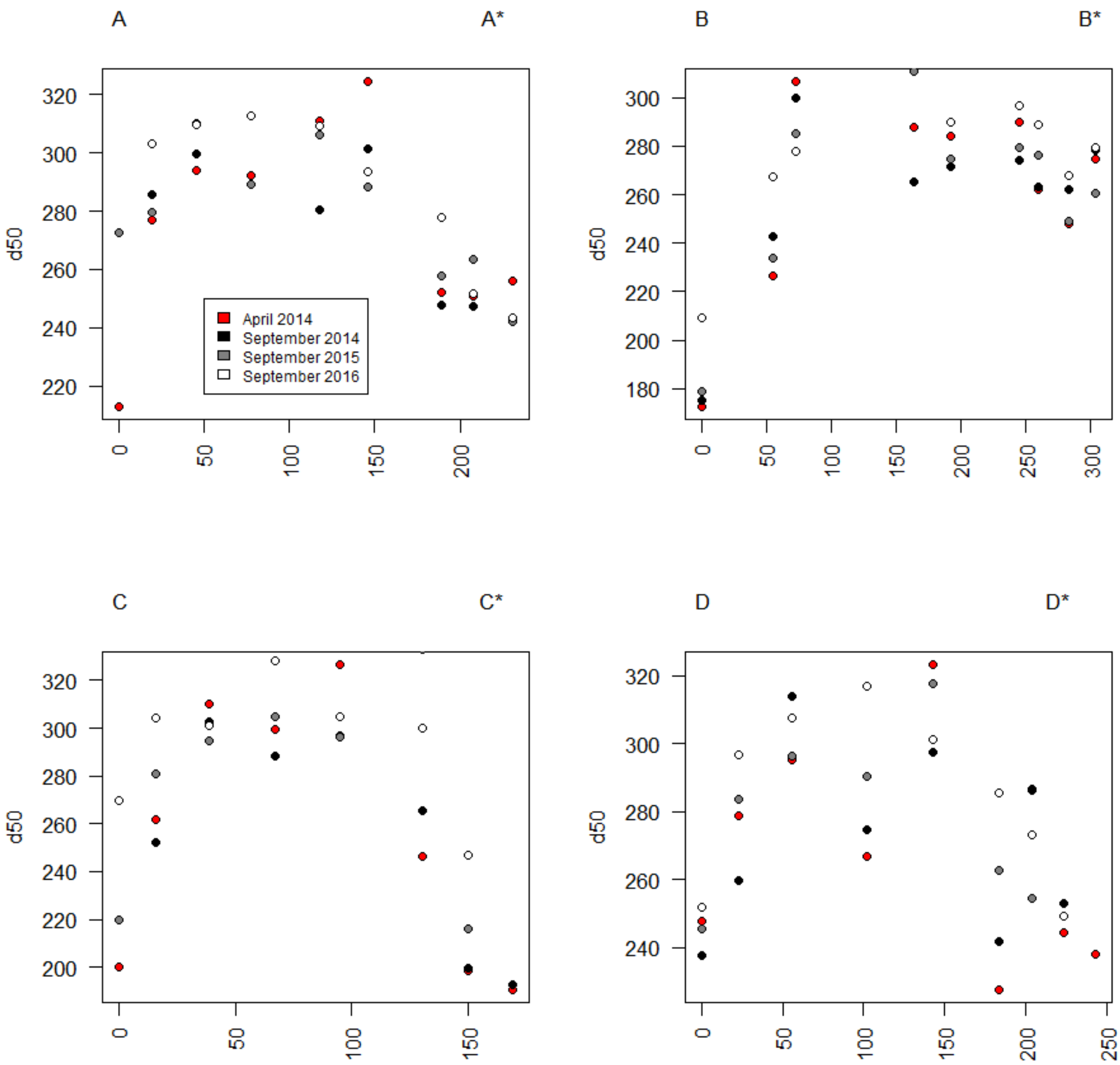


Figure 42. Change in median grain size (d50, µm) along four transects on the main sand nourishment. See Figure 2 for the position of the transects.

Species richness and total density of benthic macrofauna was in general higher at the sheltered sides of the transects in September 2015, especially along transects A-A* and B-B*. Transects C-C* and D-D* had much lower densities compared to transects A-A* and B-B*. Benthic communities differed between transects A-A*, B-B* and C-C*, D-D*. At transects A-A* and B-B* the sheltered side had high densities of *Peringia ulvae*, *Cerastoderma edule* and *Aphelochaeta marioni* (Figure 44, Figure 45). Also *Limecola balthica* was observed in high densities, but this species also occurred at the exposed side of the transects and along transects C-C* and D-D*. At transects C-C* and D-D* *Pygospio elegans* and *Bathyporeia* spp. were common, the latter especially at the exposed sides (Figure 45).

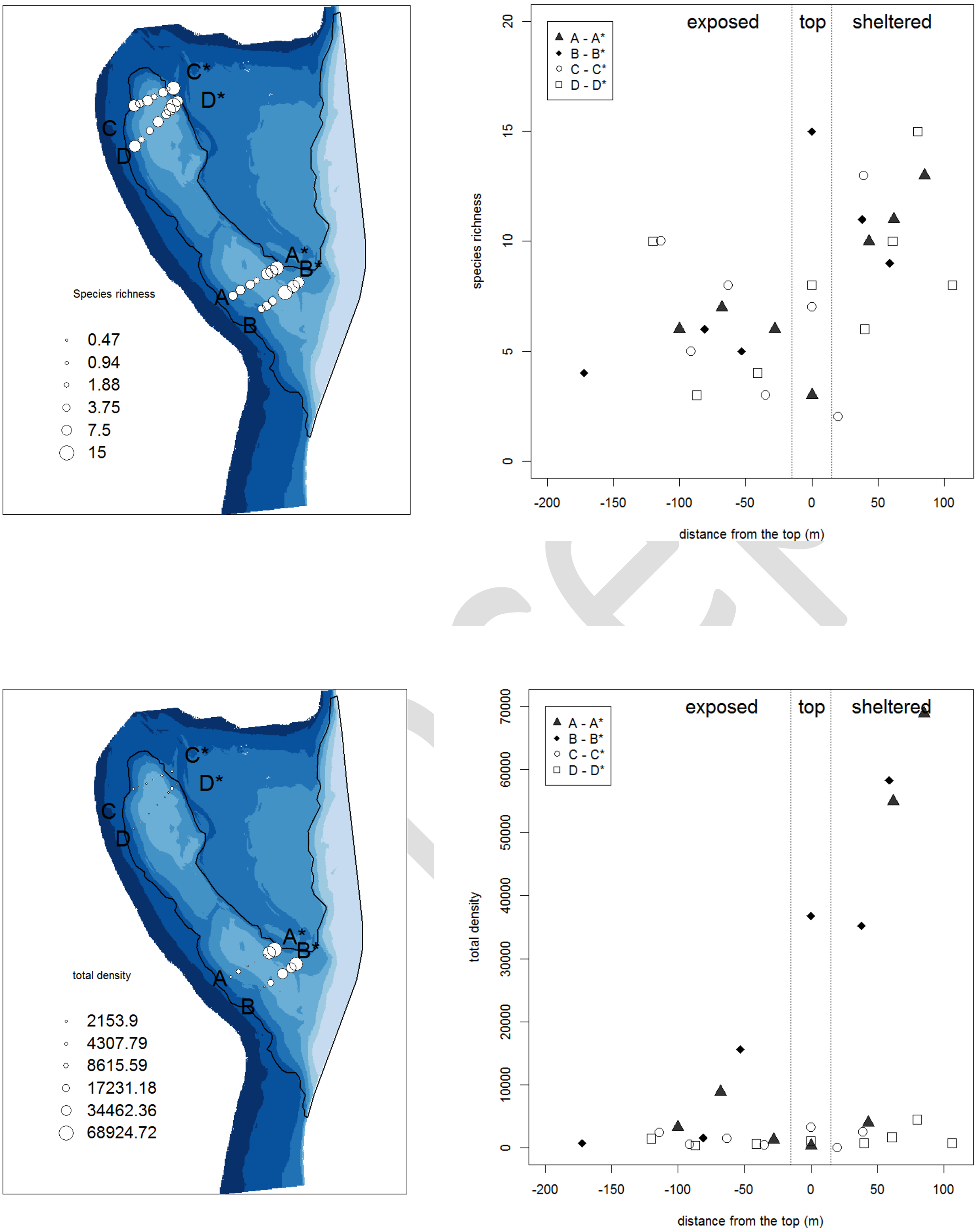


Figure 43. Species richness and total density (ind.m^{-2}) of benthic macrofauna along four transects on the main sand nourishment in September 2015.

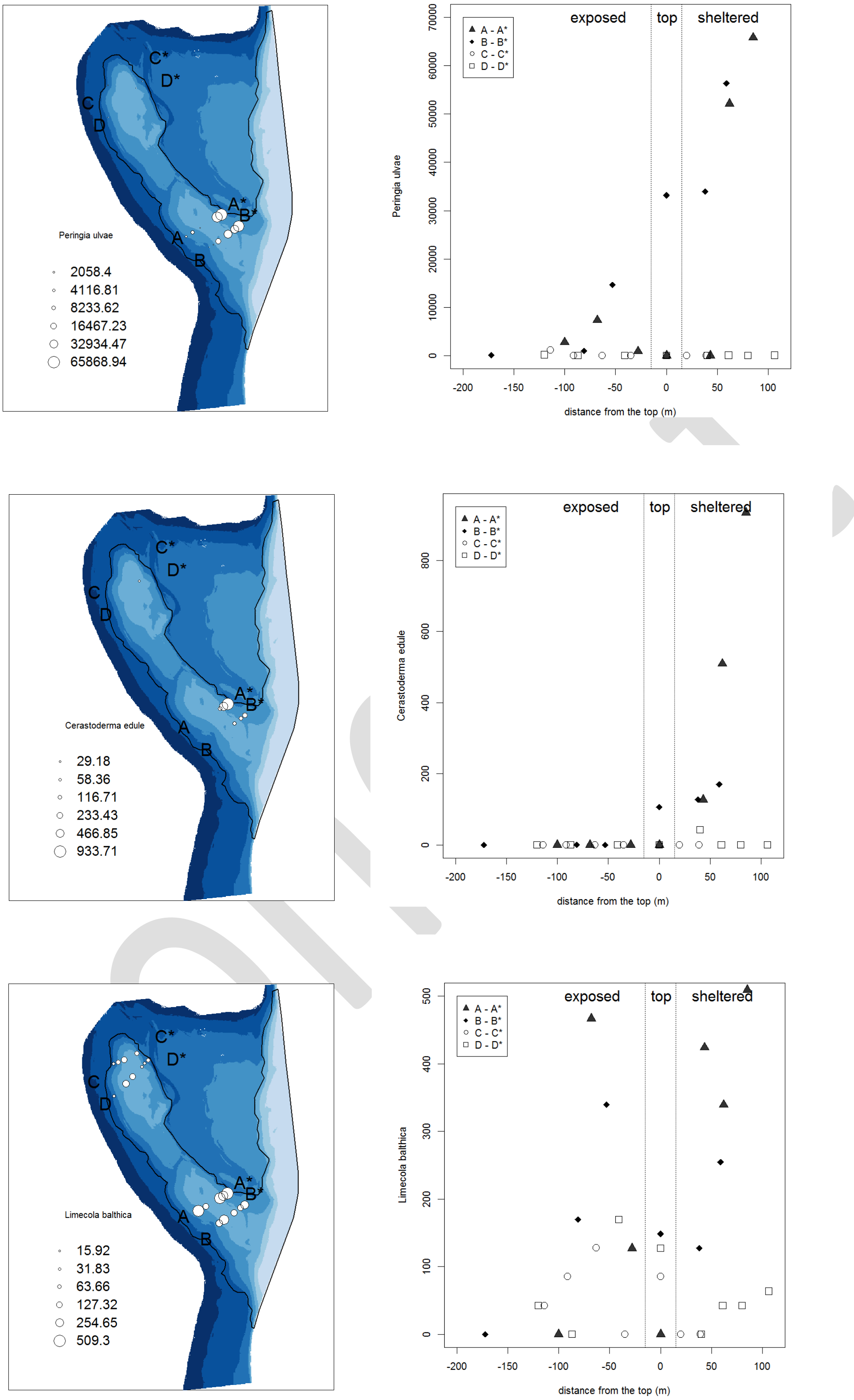


Figure 44. Density of *Peringia ulvae, Cerastoderma edule* and *Limecola balthica* (ind.m^{-2}) along four transects on the main sand nourishment in September 2015.

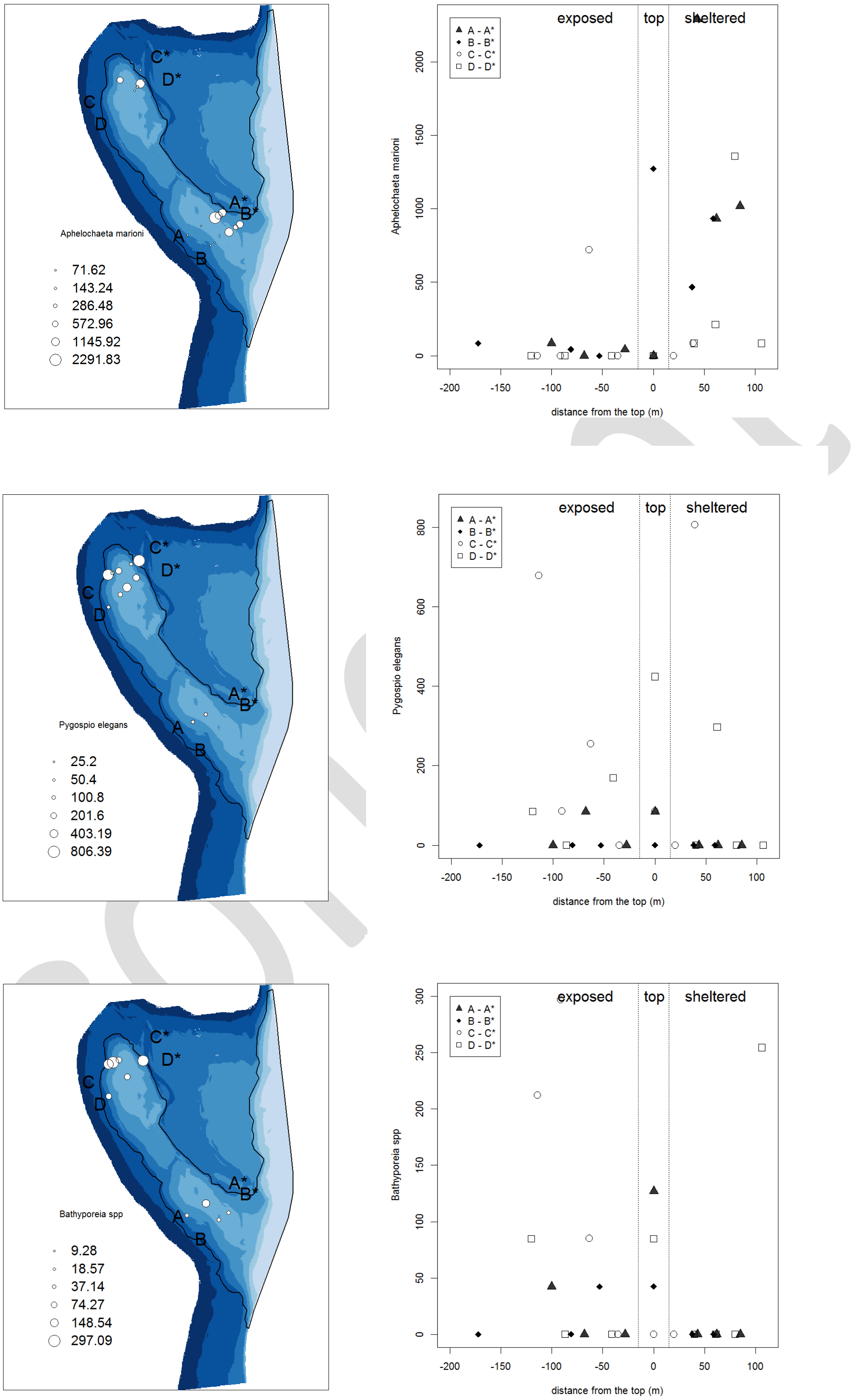


Figure 45. Density of *Aphelochaeta marioni*, *Pygospio elegans* and *Bathyporeia* spp. (ind.m^{-2}) along four transects on the main sand nourishment in September 2015.

Occurrence of benthic hotspots and coldspots

The hotspot and coldspot analysis of ecological richness demonstrated that there were a few areas that were statistically identified as hotspot or coldspot (Figure 46). Coldspots were found on the dyke foot nourishment in the northern part and on the main sand nourishment, also in the northern part. Hotspots differ from year to year, with in 2016 a hotspot area on the central tidal flat and one at the edge between the central tidal flat and the main sand nourishment.

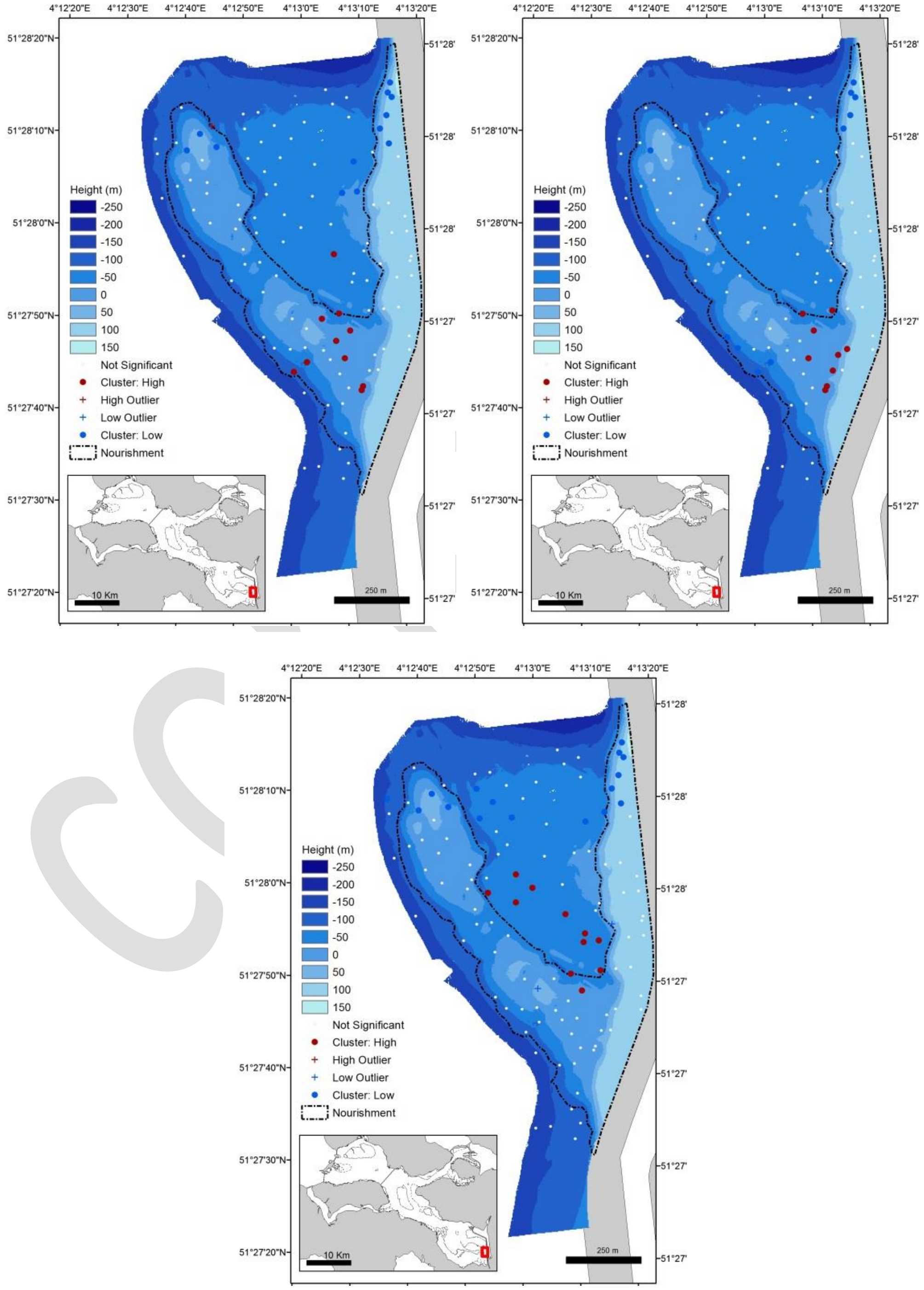


Figure 46. Spatial clustering of observed ecological richness based on Anselin local Moran's I. The size of the symbols indicates z-score values. Red dots give statistically significant hotspots, blue dots significant coldspots, white dots have no significant clustering. Top left: 2014, Top right: 2015. Bottom: 2016.

Birds

The bird counts in the winter period at low tide revealed that only two wader species used the Oesterdam area on a regular basis as foraging area, the oystercatcher *Haematopus ostralegus* and the curlew *Numenius arquata* (Figure 47). Oystercatchers foraged on average most on the central tidal flat and on the main sand nourishment, less in the reference area and least on the dyke foot nourishment. Already in the winter of 2014, Oystercatchers made use of the nourishment as foraging area, but there is no clear trend over time. Curlews foraged on average most in the reference area, although the central tidal flat and main sand nourishment were also used as foraging area. Like for the Oystercatcher, Curlews foraged least on the dyke foot nourishment. Foraging birds were already observed in the winter of 2014, but again no clear trend was seen over time.

Other waders like Dunlin (*Calidris alpina*), Redshank (*Tringa totanus*) and Grey Plover (*Pluvialis squatarola*) were mostly restricted to the reference area more to the south of the Oesterdam (Figure 47) and were only rarely seen on the central tidal flat or the nourished areas. Other wader species are rare in het whole area.

Two ducks/geese species were abundant in the Oesterdam area, the Shellduck (*Tadorna tadorna*) and the Brent Goose (*Branta bernicla*). Shellducks were most abundant on the central tidal flat, but it also frequently used the main sand nourishment as foraging area (Figure 48). Shellducks use less the reference area and the dyke foot nourishment as foraging area. Brent geese used all areas to forage on, but highest densities were observed on the central tidal flat and in the reference area. The reference area was also used as a resting area (Figure 48).

Gulls were frequently seen on the Oesterdam, with the Black-headed gull (*Chroicocephalus ridibundus*) and the European herring gull (*Larus argentatus*) as most dominant gull species. Black-headed gulls foraged mainly in the reference area and on the central tidal flat, while they used the dyke foot nourishment mainly as resting area (Figure 48). The main sand nourishment was also used as a foraging area, but in less high densities. European herring gulls used the Oesterdam area mainly as resting area, especially the nourished areas (Figure 48). Foraging birds were mainly seen on main sand nourishment and in the reference area, and to a lesser extent on the central tidal flat.

Figure 47. Bird densities (birds.ha-1) in different months in the Oesterdam area for Oystercatcher, Curlew, Dunlin, Redshank and Grey plover. C = central tidal flat; D = dyke foot nourishment; M = Main sand nourishment; R = reference area. Blue = foraging; Red = non-foraging.

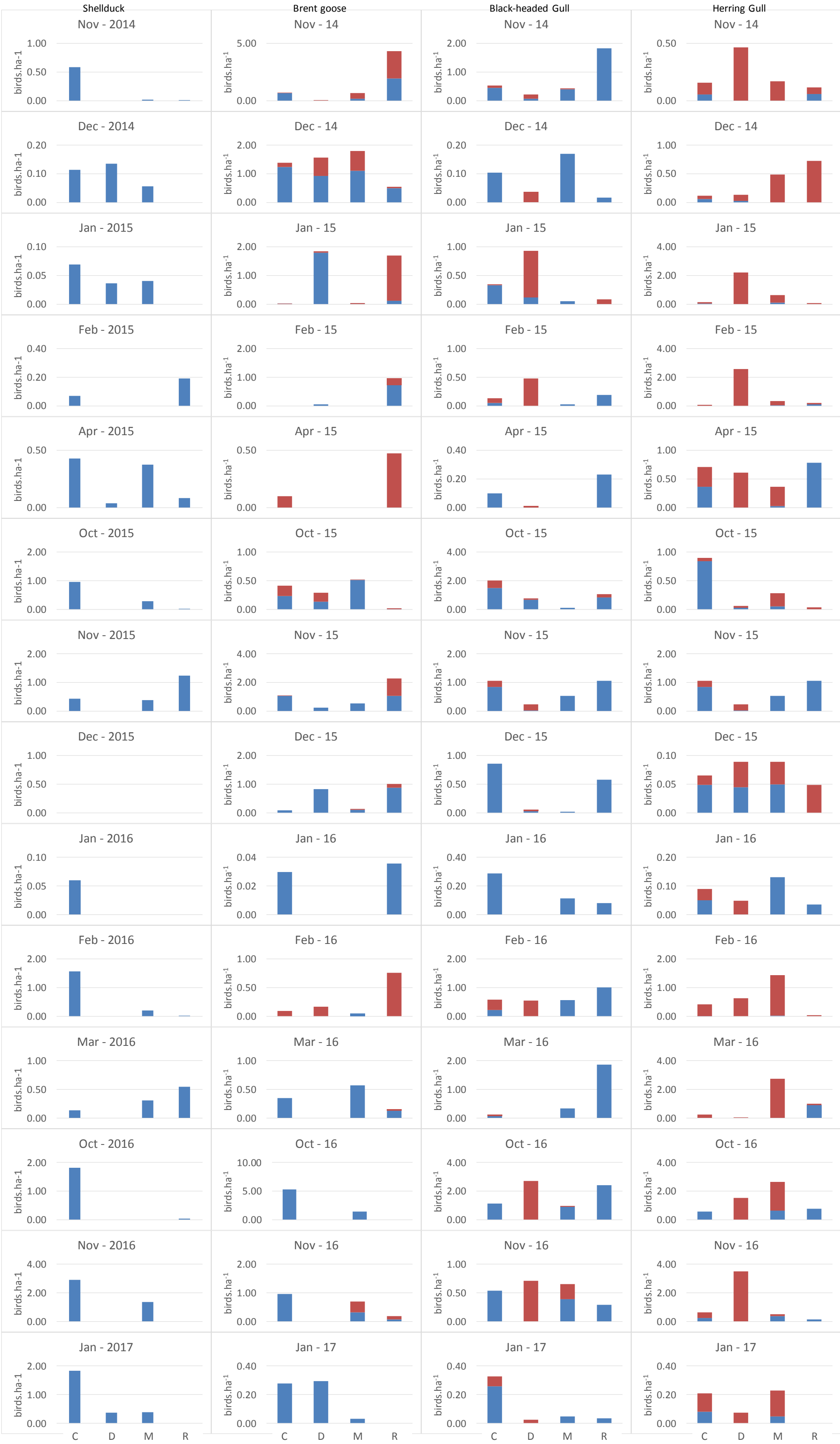


Figure 48. Bird densities (birds.ha-1) in different months in the Oesterdam area for Shellduck, Brent goose, Black-headed gull and European herring gull. C = central tidal flat; D = dyke foot nourishment; M = Main sand nourishment; R = reference area. Blue = foraging; Red = non-foraging.

Public use

While the Oesterdam area is open to the public, the area south of the nourishment is closed to the public (i.e. the reference area used for the bird counts) where people are restricted from entering onto the mudflat. The use of the Oesterdam area by the public was diverse and included walking, dog-walking (with or without leash), bait digging for worms/clams, swimming, kite and wind surfing, horse riding, etc. (pers. observ.) (Figure 49). During the bird counts disturbances were observed in all areas, including the reference area. The highest level of disturbance came from bait diggers on the central tidal flat. The more sandy nourished areas tend to be used by people to walk and take out their dog. The Oesterdam has become a hotspot for kite surfing (Figure 49).

Figure 49. Recreational use on the Oesterdam. Left: people taking out their dog. Right: kite surfing on the Oesterdam.

Mussel seed and sea grass

In 2017 mussel seed (*Mytilus edulis*) was observed on the Oesterdam, on one of the hotspot areas (Figure 50, Figure 51), covering an area of approximately 8500 m^2. Also several patches of sea grass *Zosterna noltii* were observed in 2017, both on the nourishment as on the central tidal flat, the latter coinciding with one of the hotspots for benthic macrofauna (Figure 50, Figure 51). In total 74 patches of sea grass were observed with an average size of 0.89 m^2 and an average coverage of 23% (pers. observ. Dick de Jong and Marieke van Katwijk, Appendix 5).

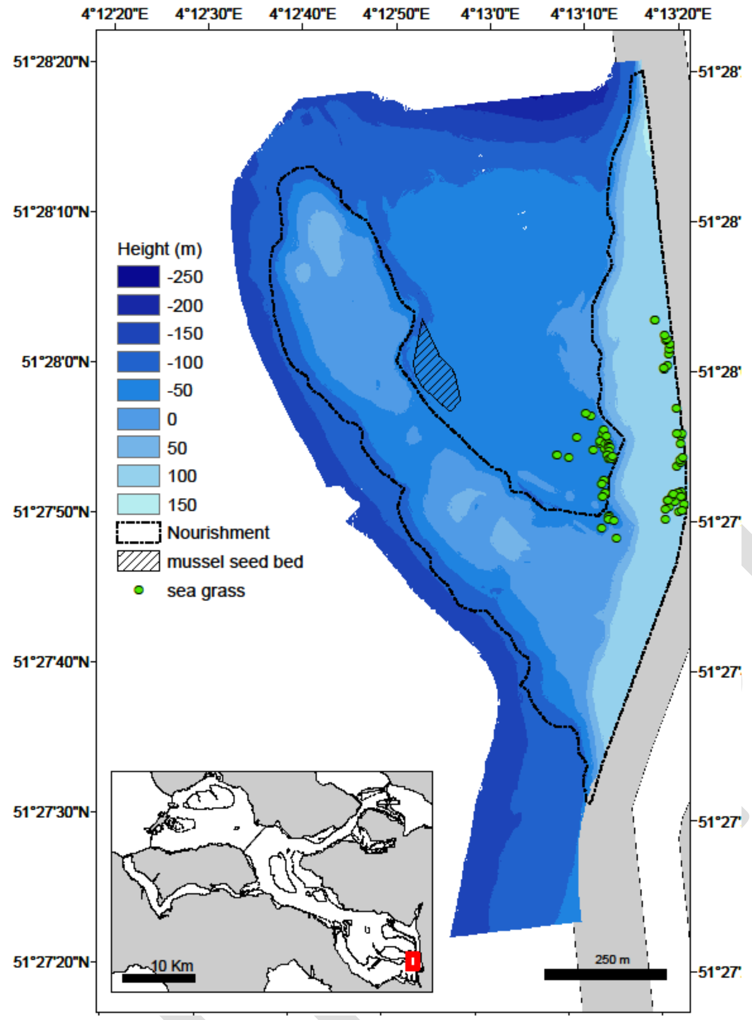


Figure 50. Occurrence of a small musselbed and sea grass *Zostera noltii* on the Oesterdam in 2017.

Figure 51. Left: mussel seed observed on the Oesterdam in 2017. Right: A patch of sea grass *Zostera noltii* on the Oesterdam in 2017.

Discussion and conclusions

Nourishment of intertidal flats to mitigate erosion is not a common management practice although in recent years, dredged material has become regarded as a potential resource and used to create and/or improve intertidal habitats (so-called beneficial use schemes) (Ray 2000, Bolam and Whomersley 2003). Relocation of dredged material from ports and navigation channels to recharge or recreate intertidal habitats is proposed as a measure to derive environmental benefits in several estuaries worldwide (Bolam 2014). This triggered several researches on the effect of sediment deposition and hypoxia on intertidal macrobenthic communities. Both manipulative field experiments (e.g. defaunation or smothering experiments) as well as large-scale interventions (e.g. recharge schemes) have indicated that intertidal benthic macrofauna communities show a high resilience to disturbances, with large numbers of early colonizers appearing within weeks or months following the impact (Zajac and Whitlach 1982, Beukema et al. 1999, Ray 2000, Bolam & Whomersley 2005, Bolam et al. 2004, 2010, Van Colen et al. 2008, 2010, Bolam 2014, van der Werf et al. 2015). So recolonization can be rapid and is sourced from a species pool already present in the surrounding, undisturbed communities. Recovery mechanisms differ and are dependent on the scale of disturbance in intertidal habitats (Zajac et al. 1998, Norkko et al. 2006). Fast adult migration is the predominant recovery mechanism at smaller scales (<1 m^2), while colonisation of large-scale disturbed habitats is initiated and dominated by post-larval and juvenile settlement by pelagic recruits, because these stages can disperse over large areas (Günther 1992). This was also the case at the Oesterdam, where after one year the nourished areas showed high densities of mainly juvenile macrobenthic species. Given the thickness of the nourishment, and the observations shortly after the construction that no benthic life was observed in the nourished areas (pers. observ.), recolonizing individuals either arrived from the undisturbed intertidal flat surrounding the nourished areas or from the water column. As most macrobenthic species have planktonic larval stages, most likely the latter was the main dispersal mechanism at the Oesterdam.

Any estimate of recovery success, however, depends on the criteria used. This can be more traditional criteria such as species richness, abundance, biomass or community composition, but can also be based on more functional criteria based on biological traits (Van Colen et al. 2010, Bolam 2014). Furthermore, recovery will vary with *measure-dependent* variables (e.g. thickness of the sediment disposal, sediment properties of the disposal, timing and design of the nourishment) and *location-dependent* variables (e.g. bed level, hydrodynamics, salinity) (e.g. Bolam et al. 2010). This implies that measuring recovery success based on a comparison with a suitable reference area is often problematic, as identical conditions are hard to find in intertidal habitats. The nourishment on the Oesterdam resulted in a significant change in elevation and therefore emersion time, most likely affecting community composition. On top of that, sediment grain size increased on the nourished areas due to the use of more coarse sediment, also possible affecting the community composition. Comparing the nourished areas (main sand nourishment and dyke foot nourishment) with the undisturbed intertidal flat (central tidal flat), univariate and multivariate variables showed considerable variation, in all three years considered. Communities changed from year to year, also on the central tidal flat, but after three years, i.e. in 2016, the communities on average still differ significantly between the nourished areas and the undisturbed central tidal flat. But also between the two nourished areas, the main sand nourishment and the dyke foot nourishment, differences between benthic communities were significant.

Several species showed higher densities on the nourishment compared to the undisturbed area. This is striking for a number of bivalve species, including *Cerastoderma edule*, *Limecola balthica* and the non-indigenous species *Ruditapes philippinarium*. Apparently these species found a suitable niche on the nourishment where they settled and recruited every year in relatively large numbers compared to the undisturbed central tidal flat, although on the central tidal flat, near the nourished areas also successful settlement of new recruits was observed, especially in 2016. The explanation for this successful settlement of bivalves on the nourished areas can be due to several factors. Firstly, the lack of large bioturbating animals on the nourishment might facilitate the settlement of other species. Especially the lack of large *Arenicola marina* could play a major role. Through bioturbation, i.e. reworking of the sediment, the lugworm *A. marina* increase erosion of fine particles thus decreasing sediment stability (Volkenborn et al., 2009). Moreover, deposit feeding by *A. marina* on diatoms might further reduce sediment cohesiveness (Volkenborn et al., 2009). *A. marina* also reworks surface sediments to deeper layers in the sediment. Consequently, *A. marina* likely decreases larval settlement, increases burial of larvae and/or increases resuspension of macrozoobenthos recruits. Several studies observed indeed negative effects of *A. marina* on post-larvae and juveniles of *C. edule* and several other species due to sediment reworking activities and repeated burying by faecal castings (Flach 1992, Whitton et al. 2016). Secondly, the change in sediment properties, tidal emersion and flow on the nourishment might also play a role in the higher number of certain species on the nourishment. It is striking to see that in the area where the main sand nourishment is attached to the dyke foot nourishment, the highest densities are observed for several species. Apparently, here conditions are more favourable, which could possibly be related to more calm hydrodynamic conditions.

The spatial distribution of ecological richness and coldspots and hotspots clearly showed that recovery of the benthic macrofauna on the nourished areas appeared heterogeneous. Some areas on the nourishment showed a high rate of recolonization, other areas showed only little recovery. Also within the two subareas, the main sand nourishment and the dyke foot nourishment, variability in recolonization is large, so recolonization of certain benthic macrofaunal species cannot only be attributed to changes in elevation (emersion time) or changes in sediment composition on the nourishment. Apparently favourable conditions were created on the nourishment, especially in the area where the main sand nourishment is connected to the dyke foot nourishment. This area can be considered as more sheltered, as it is in the lee side of the main sand nourishment. Less favourable conditions, based on a lower ecological richness and the presence of coldspots, can be found on the tip of the main sand nourishment and the northern part of the dyke foot nourishment. Here conditions seem to be more dynamic.

Also on the central tidal flat an increased variability in benthic macrofauna appeared. This is clearly visible in the hotspot analysis, where in 2016 an area at the lee side of the main sand nourishment was identified as hotspot area with a high ecological richness and an area in the northwest as ecological coldspot. The reason for the overall decrease in *Arenicola marina* numbers in 2015 and especially 2016, observed in the detailed monitoring as well as in the area-wide inventory, is unknown. Especially the fact that this was also observed on the central tidal flat was unexpected.

Although behind the scope of the original monitoring, it was an unexpected observation to see a young mussel bed (*Mytilus edulis*) and sea grass patches of *Zostera noltii* appearing in the early summer of 2017. Intertidal mussel beds are hardly found in the Oosterschelde, except for mussels found in oyster reefs (*Crassostrea gigas*). This young mussel bed was observed on the central tidal flat, at the lee side of the main sand nourishment. The area corresponded with the hot spot area observed in 2016, this is an area with a high ecological richness. In this area also high densities of the cockle *Cerastoderma edule* and the polychaete *Aphelochaeta marioni* were observed. Sea grass *Zostera noltii* has become a relatively rare species in the Oosterschelde, with the most nearby population found at Roelshoek. Most likely the observed population observed at the Oesterdam nourishment was established through seed dispersal.

The nourishment was constructed in order to conserve and restore the natural value of the area for Natura2000 bird species. This concerns mainly wader species that use the intertidal flats to forage on during low tide. Bird counts showed that Oystercatcher and Eurasian Curlew were foraging in the Oesterdam study area. Oystercatchers were foraging most on the central tidal flat and on the main sand nourishment, less in the reference area and least on the dyke foot nourishment. Already in the winter of 2014, Oystercatchers make use of the nourishment as foraging area, but there is no clear trend over time. Curlews foraged on average most in the reference area, although the central tidal flat and main sand nourishment are also used as foraging area. Like for the Oystercatcher, Curlews forage least on the dyke foot nourishment. Foraging birds are already observed in the winter of 2014, but again no clear trend was seen over time. Other waders like Dunlin (*Calidris alpina*), Redshank (*Tringa totanus*) and Grey Plover (*Pluvialis squatarola*) were mostly restricted to the reference area more to the south of the Oesterdam and are only rarely seen on the central tidal flat or the nourished areas. Other wader species are rare in het whole area. The reason for the absence of these other wader species can be twofold. Firstly, disturbance on the Oesterdam is frequent, as was observed during the bird counts or other visits. Bait digging, walking, but also kite surfing causes a relatively high disturbance pressure on the area, which will certainly affect bird presence. Secondly, the reference area to the south of the Oesterdam is more silty, most likely resulting in a different benthic community, which could be more favourable food for the other wader species. Unfortunately, the benthic community structure was not investigated in the reference area, but from the few sampling stations that were sampled in 2014, 2015 and 2016 south of the nourishment, is was shown that indeed the benthic macrofauna in these more muddy locations differed, with a dominance of polychaetes like *Aphelochaeta marioni*, *Hediste diversicolor* and *Notomastus latericeus*.

In conclusion, the Oesterdam nourishment showed a fast recolonization of benthic macrofauna. After one year (2014) already species richness and abundance was similar or higher on the nourished areas, although biomass on average was still lower compared to the undisturbed central tidal flat. The following years (2015, 2016) the recovering community still differed from the ambient, undisturbed, sediments due to enhanced recruitment success of long-lived species (i.e. bivalves *Cerastoderma edule* and *Limecola balthica*), presumably resulting from the lowered interference from bioturbation during early recovery stages in the nourished areas. Recolonization appeared patchy, with large spatial variability. Some areas could be identified as ecological hotspots with a high ecological richness; these areas were situated in the more sheltered, lee side of the main sand nourishment and dyke foot nourishment (Figure 52). In the same areas the mussel bed and sea grass patches were observed in 2017. Other areas were identified as ecological coldspots with a low ecological richness; these were the more exposed areas on the main sand nourishment and the dyke foot nourishment. Also the nourishment had an indirect effect on the benthic community of the undisturbed central tidal flat, as ecologically rich areas were created at the lee side of the main sand nourishment.

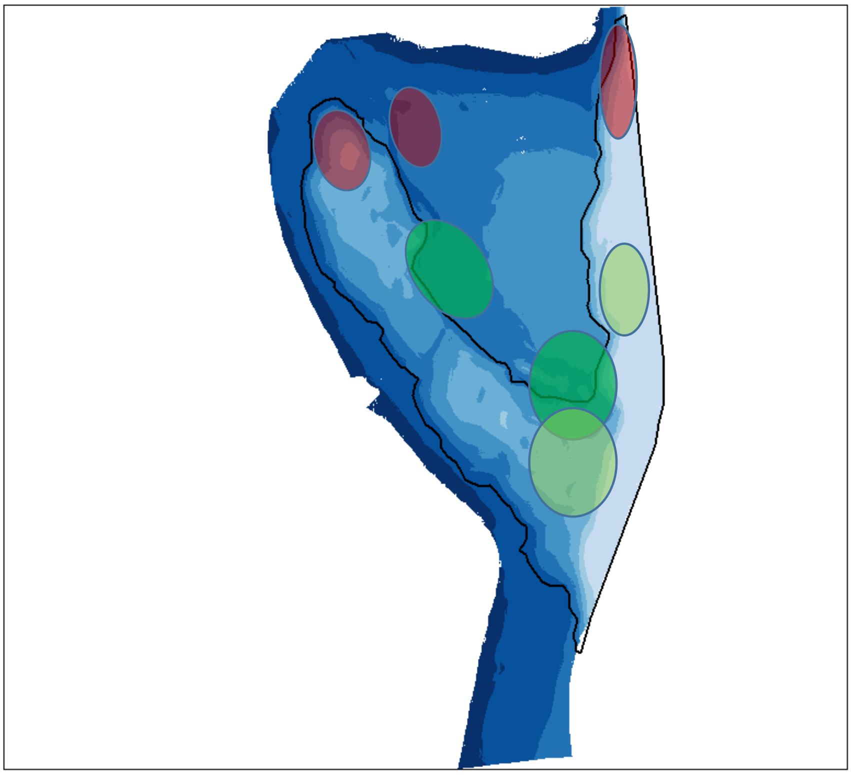


Figure 52. Ecologically rich and ecologically poor areas on the Oesterdam in 2016, based on all information on benthic macrofauna. Dark green: very rich; Green: rich; Red: poor.

With respect to birds, Oystercatchers and Eurasian Curlews used the Oesterdam as foraging area, including the nourished areas (especially the main sand nourishment). Other wader species were hardly observed, although they were frequently seen foraging south of the Oesterdam study area. The relatively fast recolonization of the benthic macrofauna, and especially the occurrence of several bivalve species and *Peringia ulvae* should be profitable for waders like Oystercatcher and Knot. Disturbance by humans could be one explaining factor, as the area is frequently used for bait digging, walking and kite surfing. These activities are allowed but are considered as a threat to the area with respect to its function as foraging area for waders. Also the observation of sea grass patches (endangered and protected species) and a mussel bed in 2016 needs further consideration and might need some additional measures in relation to the human disturbances in the area.

Three years of monitoring the recolonization and recovery of the benthic macrofauna is still short, and the long-term evolution (> 5 years) of the benthic macrofauna needs to be assessed to determine the exact functioning of this area as foraging ground for birds.

Acknowledgements

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Literature

Airoldi L & Beck MW 2007. Loss, status and trends of coastal marine habitats of Europe. Oceanography and Marine Biology – an annual review 45: 345-405.

Anselin L. 1995. Local Indicators of Spatial Association – LISA. Geographical Analysis 27, 93-115.

Beukema JJ, Flach EC., Dekker, R., Starink, M., 1999. A long-term study of the recovery of the macrozoobenthos on large defaunated plots on a tidal flat in the Wadden Sea. J. Sea Res. 42: 235-254.

Bolam SG. 2014. Macrofaunal recovery following the intertidal recharge of dredged material: A comparison of structural and functional approaches. Marine Environmental Research 97: 15-29.

Bolam SG, Whomersley P. 2003. Invertebrate recolonisation of fine-grained beneficial use schemes: an example from the south-east coast of England. J. Coast. Conserv. 9: 159-169.

Bolam SG, Whomersley P, 2005. Development of macrofaunal communities on dredged material used for mudflat enhancement: a comparison of three beneficial use schemes after one year. Mar. Pollut. Bull. 50: 40-47.

Bolam SG, Schratzberger M, Whomersley P. 2004. Macrofaunal recolonization in intertidal mudflats: the effect of organic content and particle size. J. Exp. Mar. Biol. Ecol. 306: 157-180.

Bolam SG, Barry J, Schratzberger M, Whomersley P, Dearnaley M. 2010. Macrofaunal recolonisation following the intertidal placement of fine-grained dredged material. Environ. Monit. Assess. 168 (1e4): 499-510.

Clarke KR and Warwick RM. 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratory, Plymouth, UK, 144 pp.

Cozzoli, F, TJ Bouma, T Ysebaert, PMJ Herman. 2013.). Application of non-linear quantile regression to macrozoobenthic species distribution modelling: comparing two contrasting basins Mar. Ecol. Prog. Ser. 475: 119-133. hdl.handle.net/10.3354/meps10112

de Ronde J, JPM Mulder, LA van Duren, T Ysebaert. 2013. Eindadvies ANT Oosterschelde (Concluding Advice Autonomous Negative Trend Oosterschelde), Deltares Report 1207722-000-ZKS-0010.

de Vet PLM, Prooijen BC van, Wang ZB. 2017. The differences in morphological development between the intertidal flats of the Eastern and Western Scheldt. Geomorphology. doi: 10.1016/j.geomorph.2016.12.031.

De Vriend, H.J., ZB Wang, T Ysebaert, PMJ Herman, P Ding. 2013. Eco-Morphological Problems in the Yangtze Estuary and the Western Scheldt, Wetlands, Volume 31, Issue 6 , pp 1033-1042.

Dyer KR, MC Christie and EW Wright. 2000. The classification of intertidal mudflats. Continental Shelf Research 20: 1039 - 1060.

Flach, E.C., 1992. Disturbance of benthic infauna by sediment-reworking activities of the lugworm Arenicola marina. Neth. J. Sea Res. http://dx.doi.org/10.1016/0077-7579(92)90048-J.

Friedrichs CT. 2011. Tidal Flat Morphodynamics: A Synthesis, Reference Module in Earth Systems and Environmental Sciences, Volume 3: Estuarine and Coastal Geology and Geomorphology, 2011, Pages 137–170.

Günther, C.P., 1992. Dispersal of Intertidal Invertebrates – a strategy to react to disturbances of different scales. Netherlands Journal of Sea Research 30: 45–56.

Heip CHR, Goosen NK, Herman PMJ, Kromkamp J, Middelburg JJ, Soetaert K. 1995. Production and consumption of biological particles in temperate tidal estuaries. Oceanography and Marine Biology Annual Reviews 33, 1–150.

Herman PMJ, Middelburg JJ, van de Koppel J, Heip CHR. 1999. Ecology of estuarine macrobenthos. Advances in Ecology Research 29, 195–240.

Le Hir P, Roberts W, Cazaillet O, Christie M, Bassoulet P, Bacher C (2000) Characterization of tidal flat hydrodynamics. Continental Shelf Research 20:1079-1097.

Lotze et al. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312: 1806-1809.

Mulder JPM and Louters T. 1994. Changes in basin geomorphology after implementation of the Oosterschelde estuary project. Hydrobiologia 282-283, 29-39.

Nienhuis PH and Smaal AC. 1994. Oosterschelde Estuary (The Netherlands): a case-study of a changing ecosystem. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Norkko A, Rosenberg R, Thrush SF, Whitlatch RB. 2006. Scale- and intensity-dependent disturbance determines the magnitude of opportunistic response. J. Exp. Mar. Biol. Ecol. 330:195–207.

Ray, G.L., 2000. Infaunal assemblages on constructed intertidal mudflats at Jonesport, Maine (USA). Mar. Pollut. Bull. 40: 1186-1200.

Santinelli G and De Ronde JG. 2012. Volume analysis on RTK profiles of the Eastern Scheldt, Report 1206094. Deltares.

Thrush et al. 2004. Muddy waters: elevating sediment input to coastal and estuarine habitats. Frontiers in Ecology and the Environment 2: 299-306.

van der Wal D and Herman PMJ. 2012. Ecosystem engineering effects of Aster tripolium and Salicornia procumbens salt marsh on macrofaunal community structure. Estuaries and Coasts 35: 714-726.

Van Colen C, Montserrat F, Vincx M, Herman PMJ, Ysebaert T, Degraer S. 2008. Macrobenthic recovery from hypoxia in an estuarine tidal mudflat. *Marine Ecology Progress Series* 372: 31-42.

Van Colen C, Montserrat F, Vincx M, Herman PMJ, Ysebaert T, Degraer S. 2010. Long-term divergent tidal flat community recovery following hypoxia-induced mortality. *Marine Pollution Bulletin* 60: 178-186.

van der Werf J, Reinders J, van Rooijen A, et al. 2015. Evaluation of a tidal flat sediment nourishment as estuarine management measure. Ocean Coast Manag 114:77–87. doi: 10.1016/j.ocecoaman.2015.06.006.

Volkenborn N, Robertson DM, Reise K. 2009. Sediment destabilizing and stabilizing bio-engineers on tidal flats: cascading effects of experimental exclusion. Helgol. Mar. Res. 63, 27–35.

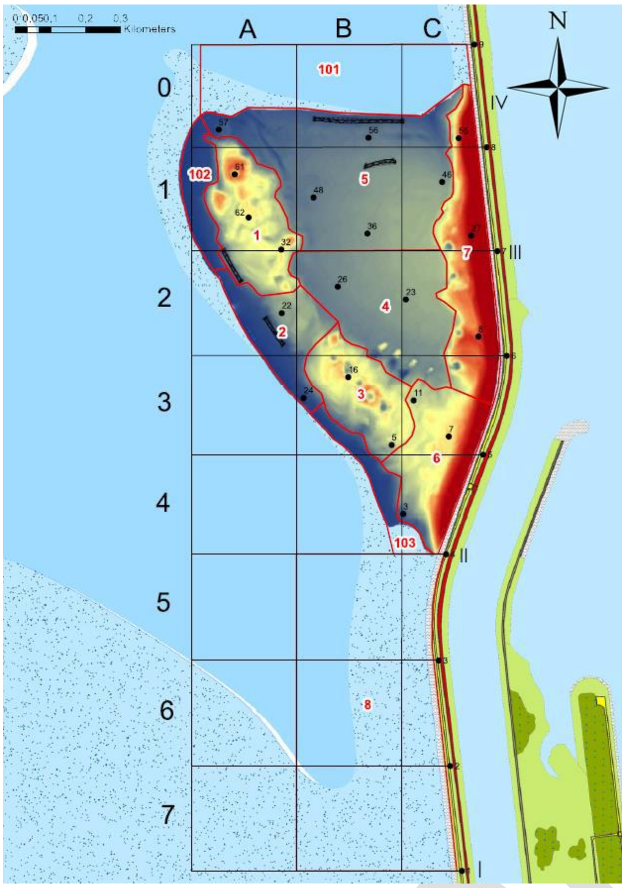
Whitton TA, SR Jenkins, CA Richardson, JG Hiddink. 2016. The effect of macrofaunal disturbance on *Cerastoderma edule* post-larvae. Journal of Sea Research 112: 23-31.

Ysebaert T, Plancke Y, Bolle L, De Mesel I, Vos G, Wielemaker A, Van der Wal D, Herman PMJ. 2009. Habitatmapping Westerschelde – Deelrapport 2: Ecologische karakteristieken en ecotopen in het subtidaal van de Westerschelde. Studie in opdracht van LTV O&M. Rapport Nederlands Instituut voor Ecologie (NIOO-KNAW), Centrum voor Estuariene en Mariene Ecologie, Yerseke.

Zajac RN, Whitlach RB. 1982. Responses of estuarine infauna to disturbance. I. Spatial and temporal variation of initial recolonisation. Mar. Ecol. Prog. Ser. 10: 1-14.

Zajac RN, Whitlatch RB, Thrush SF. 1998. Recolonization and succession in soft-sediment infaunal communities: the spatial scale of controlling factors. Hydrobiologia 375–76: 227–240.

Appendix 1. Bird plots used for bird counting.



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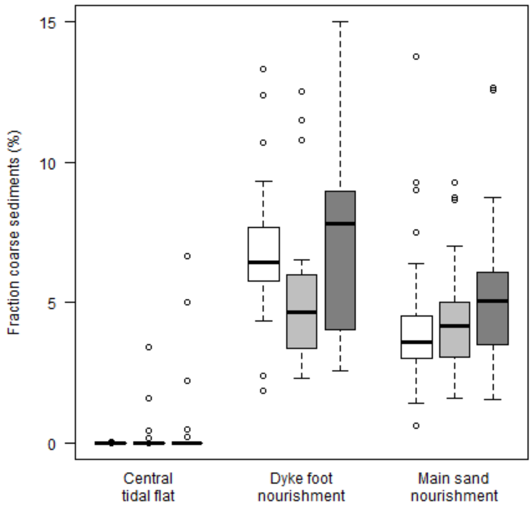
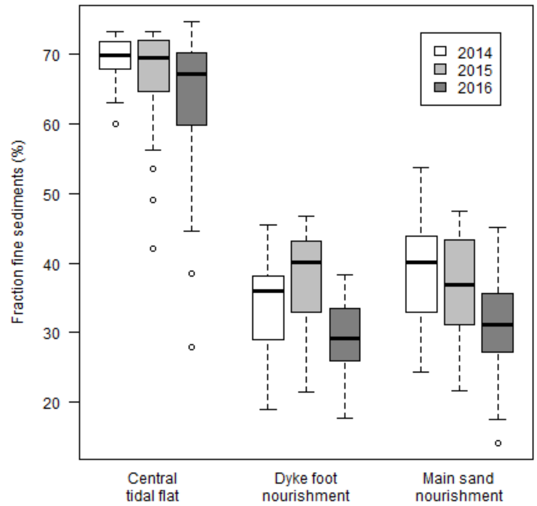
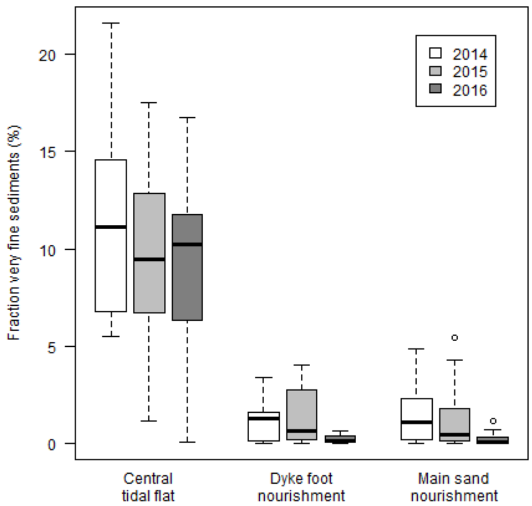
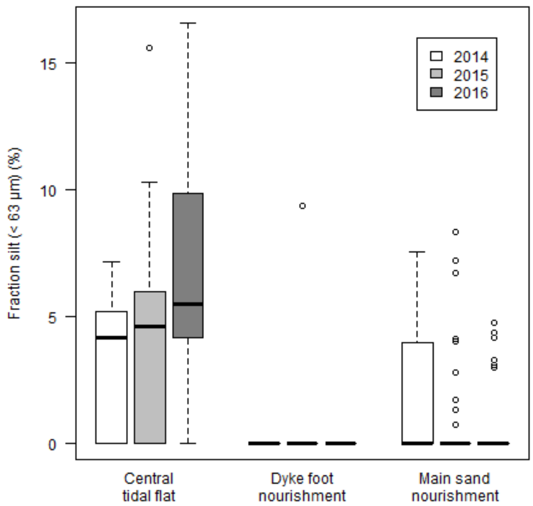
Appendix 2. Box plots of the fractions coarse, fine, very fine and silt at the Oesterdam.

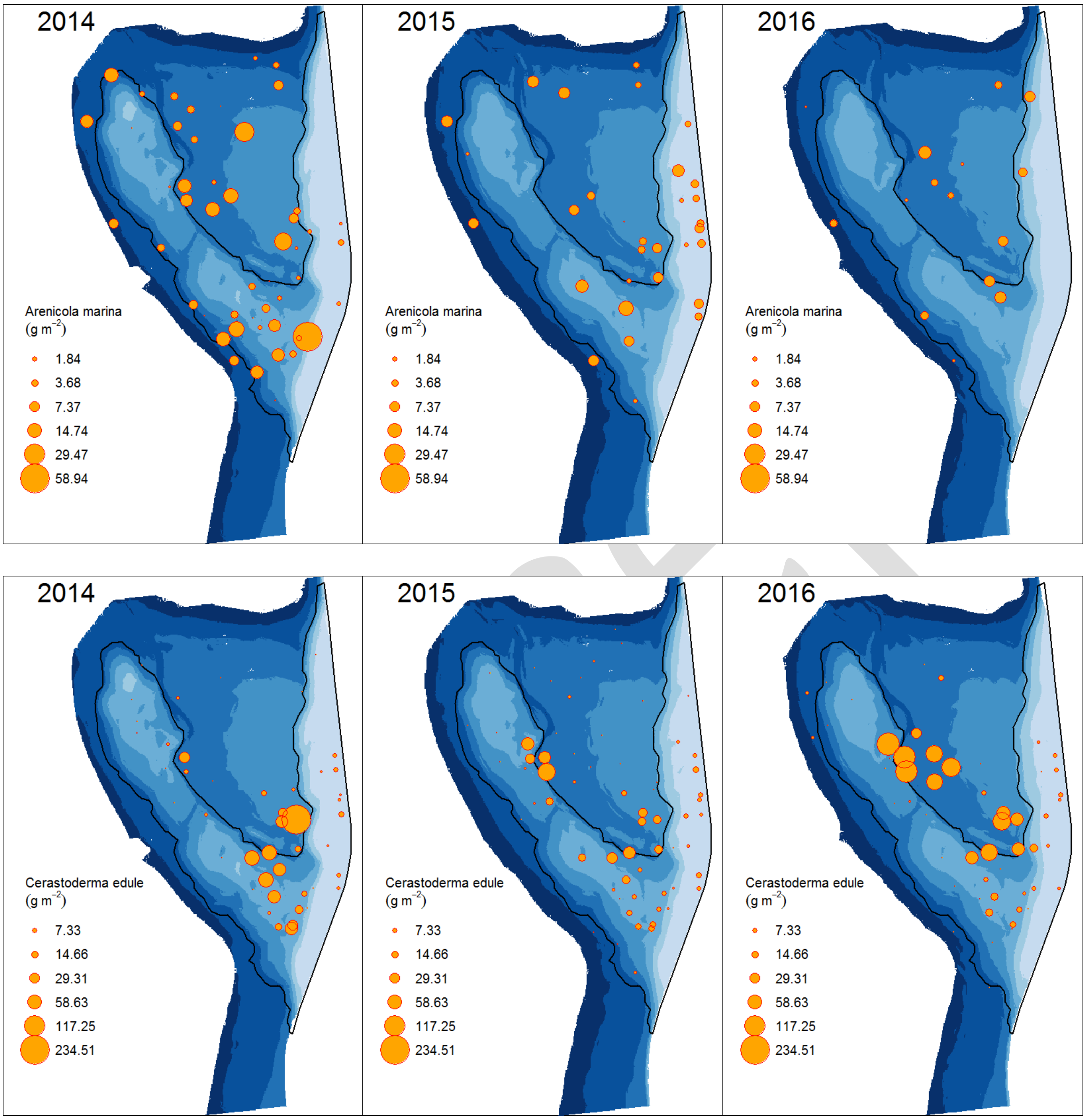


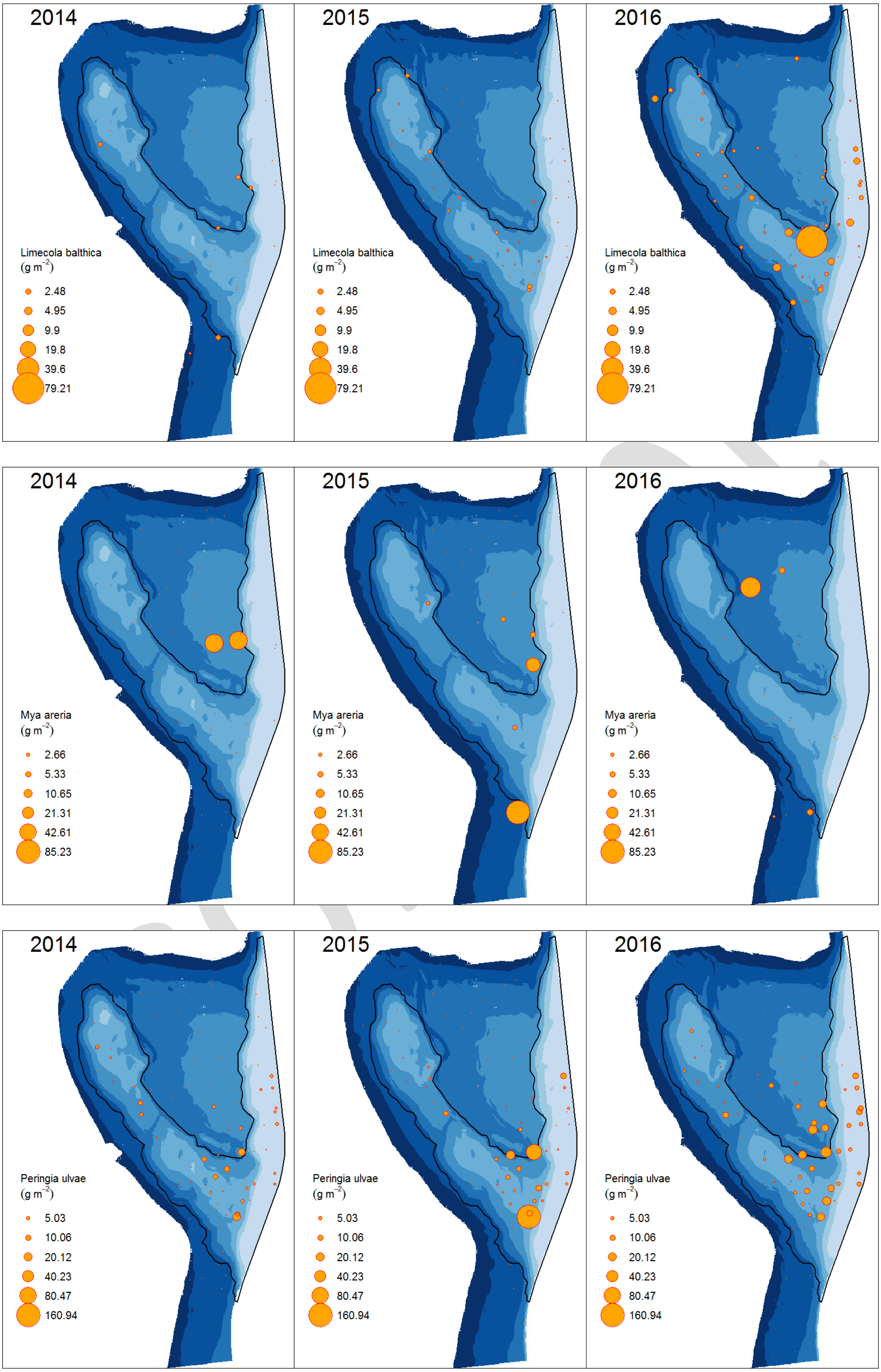


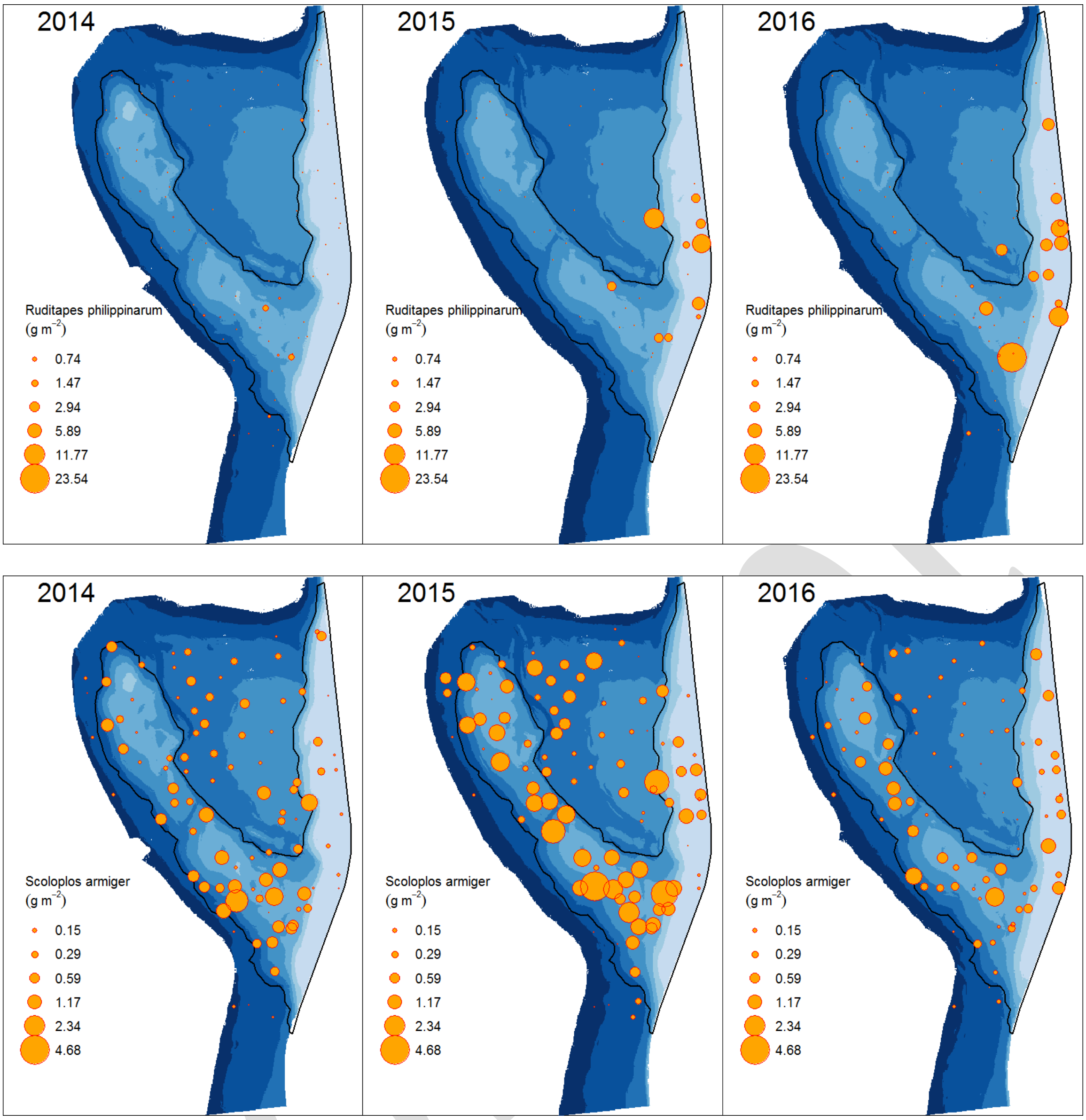




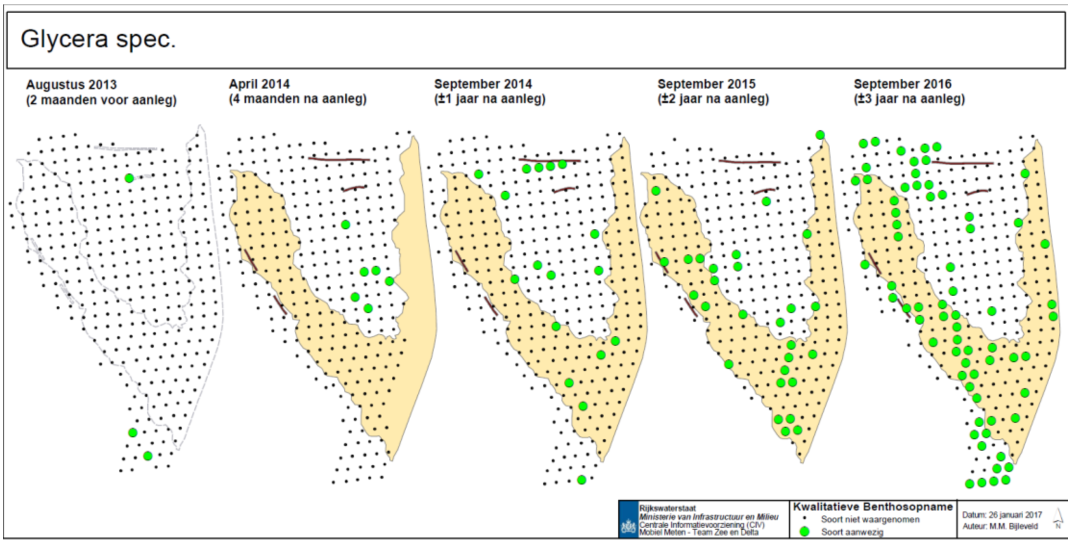
Appendix 3. Distribution maps of biomass (g AFDW.m^{-2}) of the seven most dominant species.

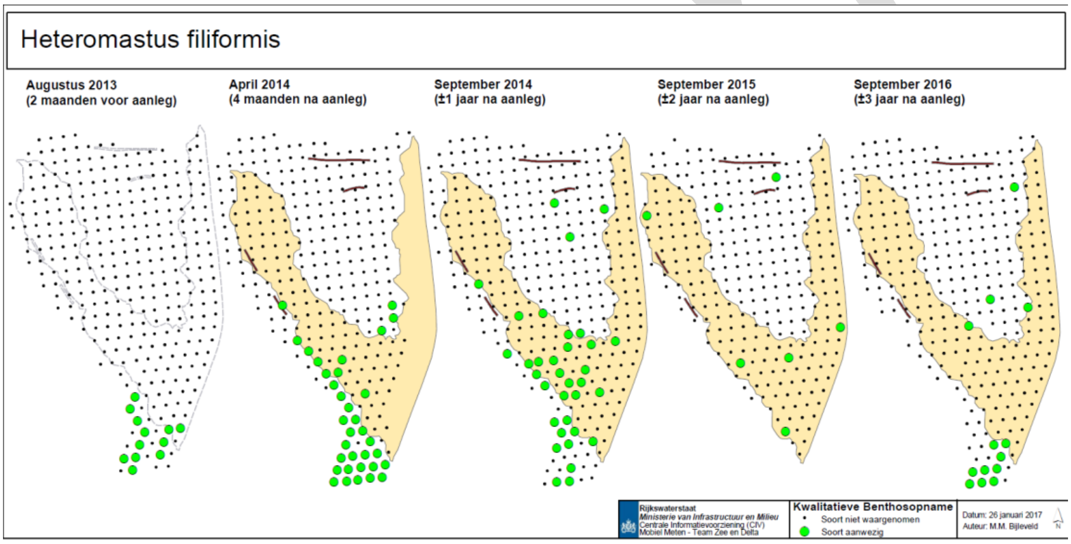


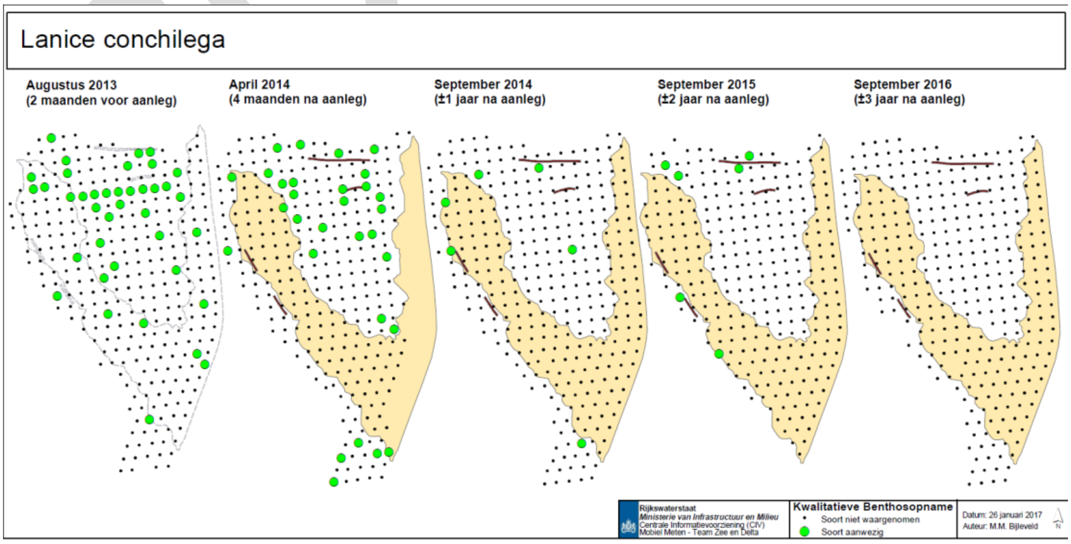

2014
2015
2016
Limecola balthica
(g m-2)
2.48
4.95
9.9
19.8
39.6
79.21
Mya areria
(g m-2)
2.66
5.33
10.65
21.31
42.61
85.23
Peringia ulvae
(g m-2)
5.03
10.06
20.12
40.23
80.47
160.94

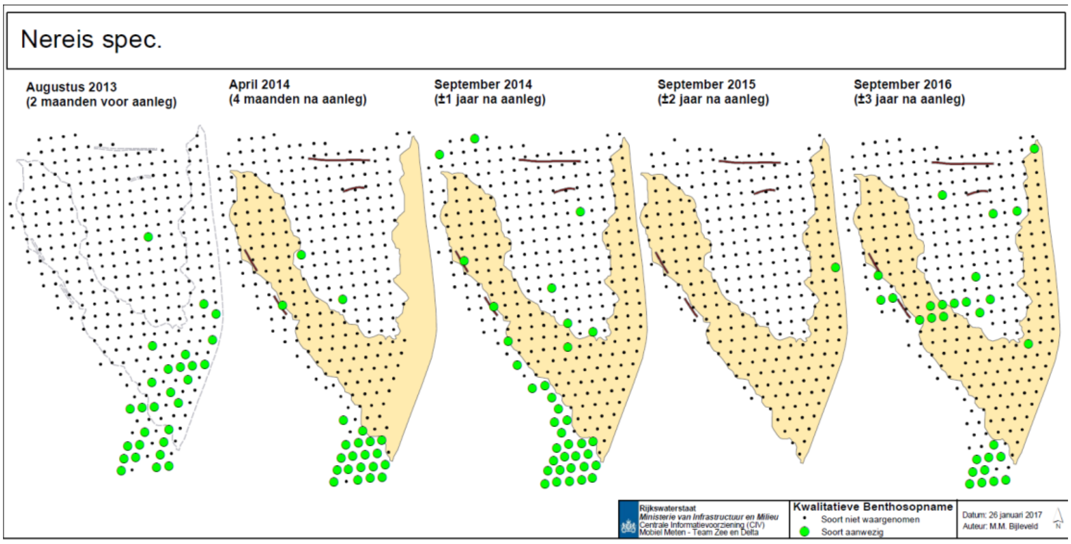

2014
2015
2016
Ruditapes philippinarum
(g m^{-2})
0.74
1.47
2.94
5.89
11.77
23.54
2014
2015
2016
Scoloplos armiger
(g m^{-2})
0.15
0.29
0.59
1.17
2.34
4.68

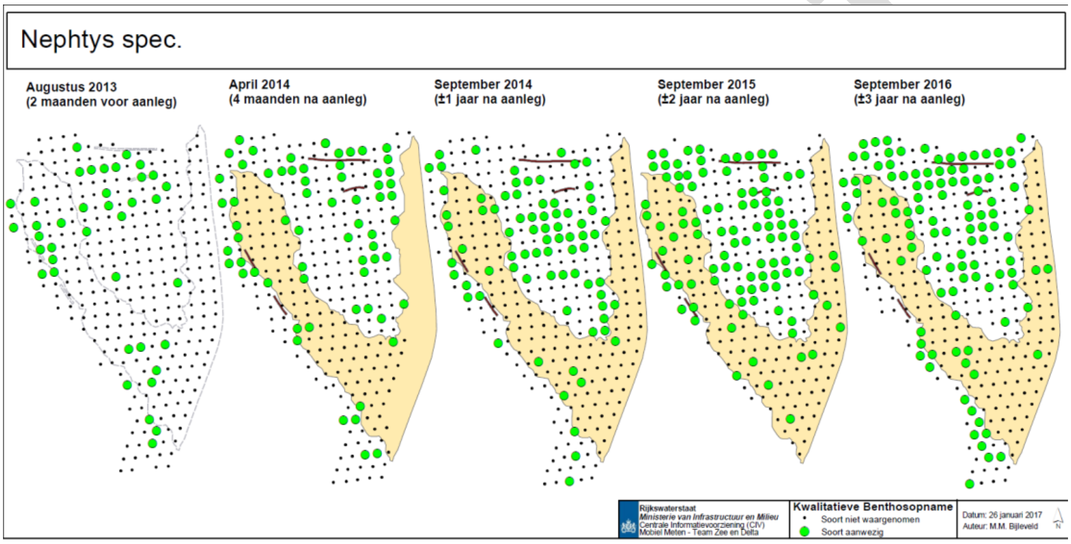
Appendix 4. Distribution maps of benthic species observed in the qualitative monitoring. Green dots = species present.








Nereis spec.
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
Ministerie van Infrastructuur en Milieu
Centrale Informatievoorziening (CIV)
Mobiel Meten - Team Zee en Delta
Kwalitatieve Benthosopname
Soort niet waargenomen
Soort aanwezig
Datum: 26 januari 2017
Auteur: M.M. Bijleveld


Nephtys spec.
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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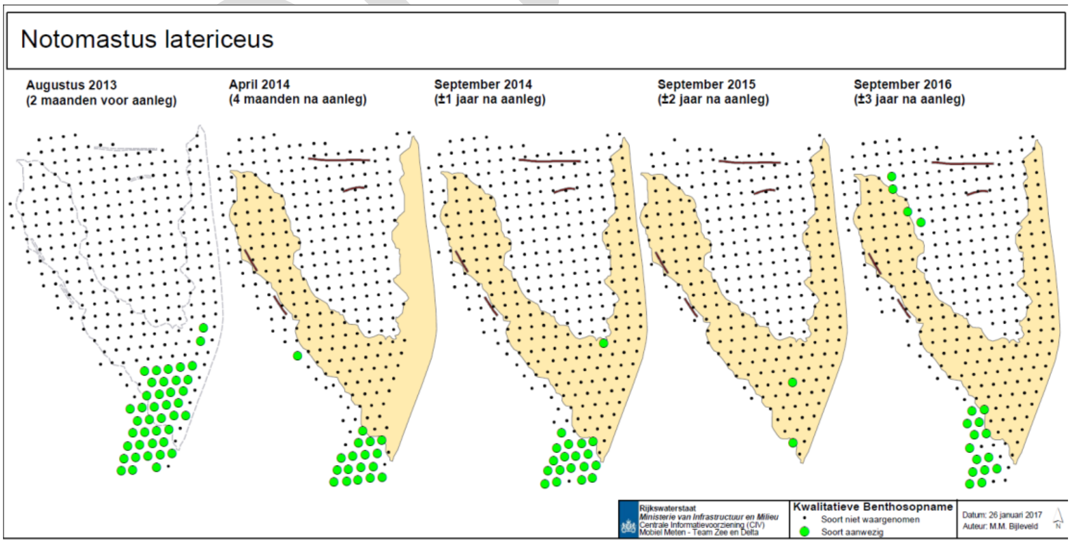
Notomastus latericeus
Augustus 2013
(2 maanden voor aanleg)
April 2014
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September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
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Soort aanwezig
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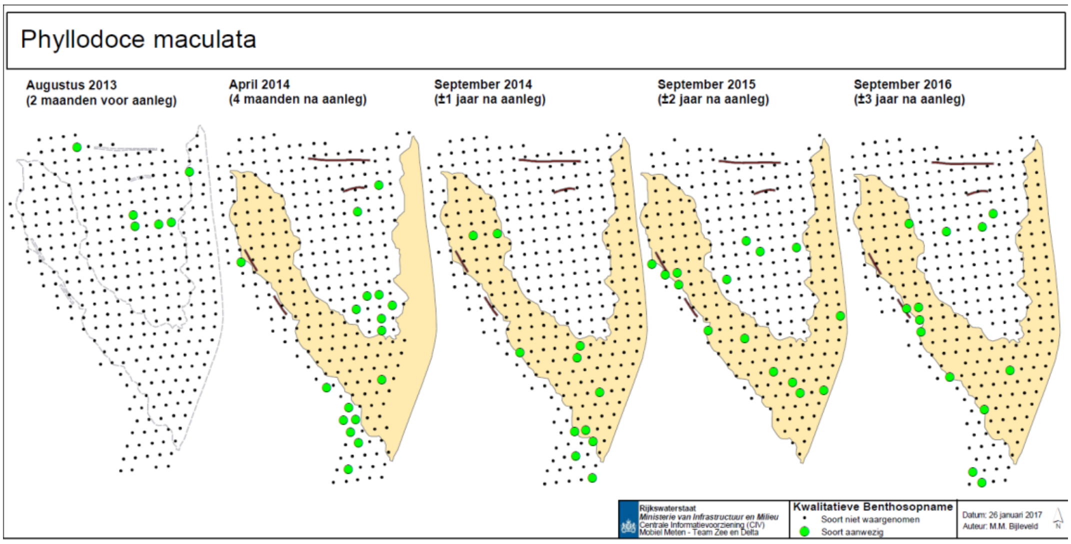
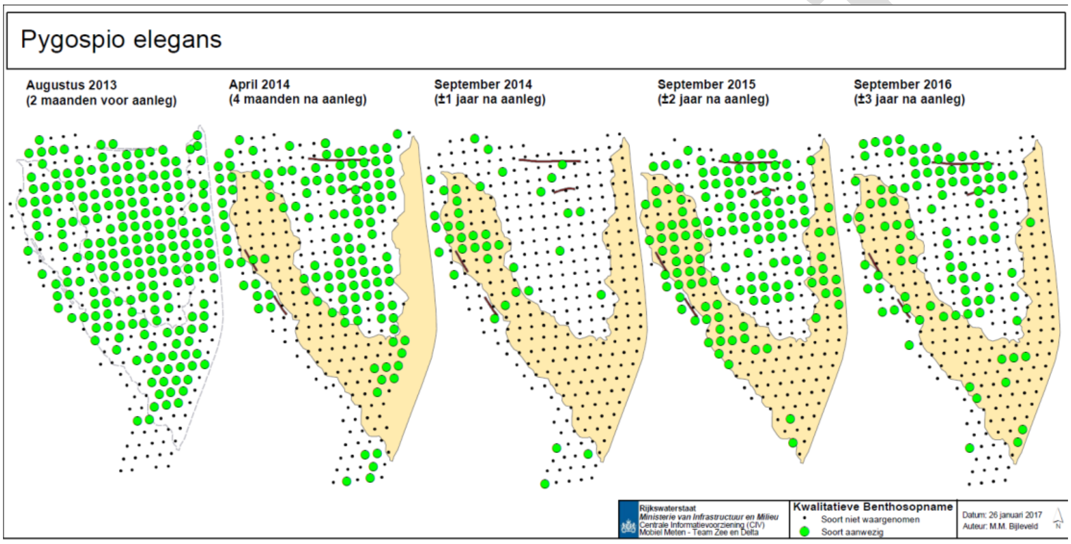

Phyllodoce maculata
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
Ministerie van Infrastructuur en Milieu
Centrale Informatievoorziening (CIV)
Mobiel Meten - Team Zee en Delta
Kwalitatieve Benthosopname
Soort niet waargenomen
Soort aanwezig
Datum: 26 januari 2017
Auteur: M.M. Bijleveld
N


Pygospio elegans
Augustus 2013
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April 2014
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September 2014
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September 2015
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September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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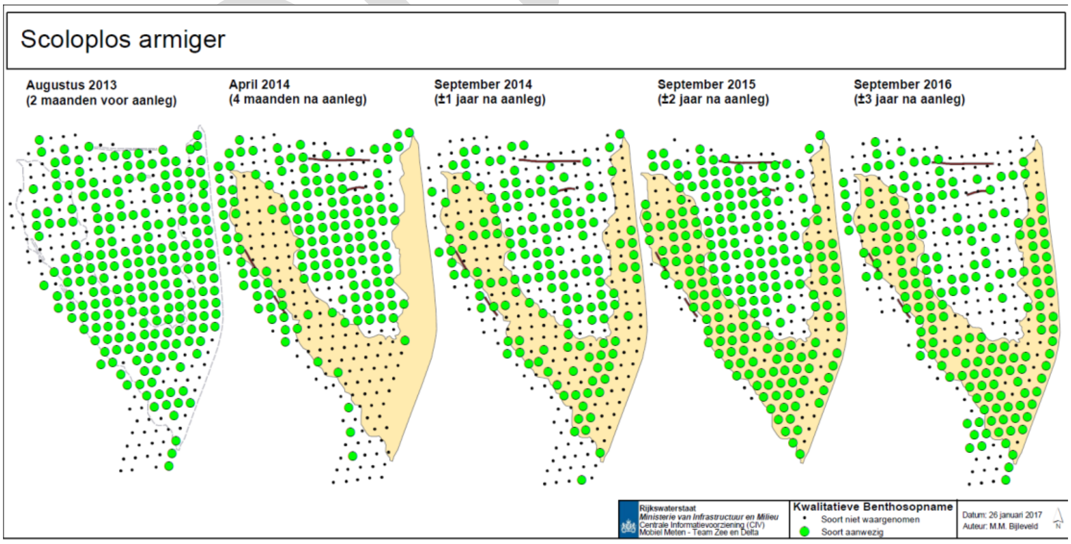
Scoloplos armiger
Augustus 2013
(2 maanden voor aanleg)
April 2014
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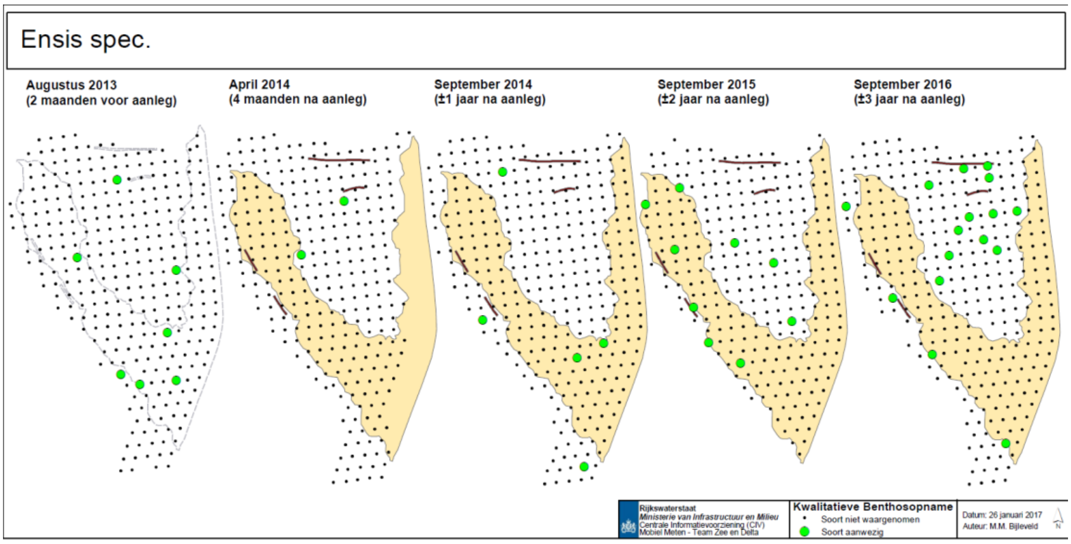

Ensis spec.
Augustus 2013
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April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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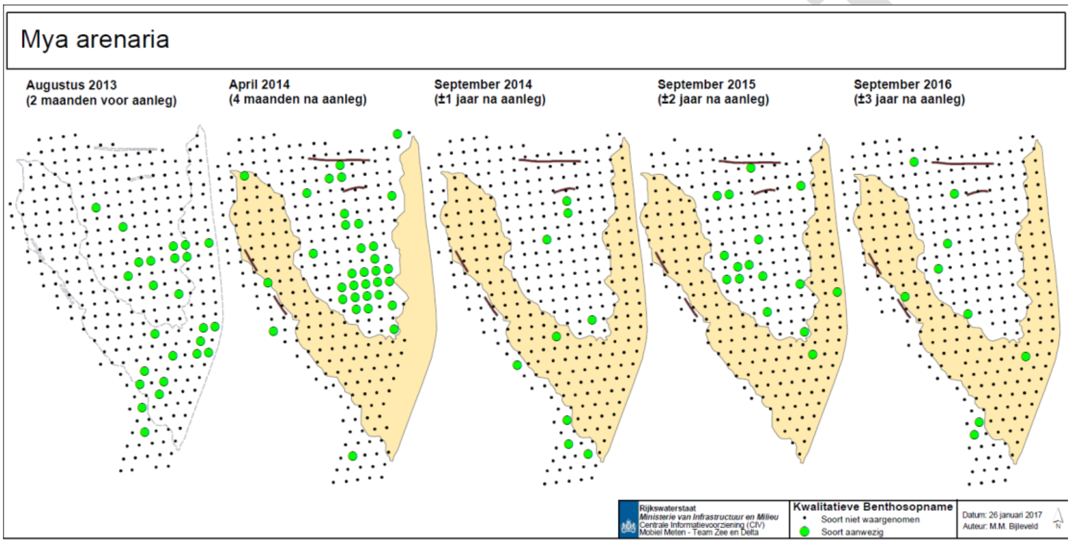

Mya arenaria
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April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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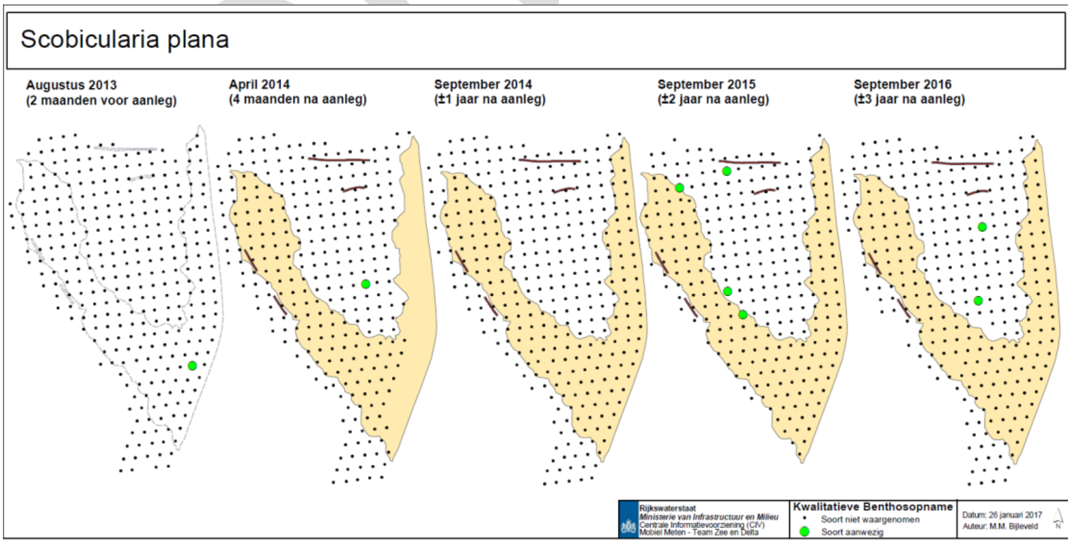

Scobicularia plana
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
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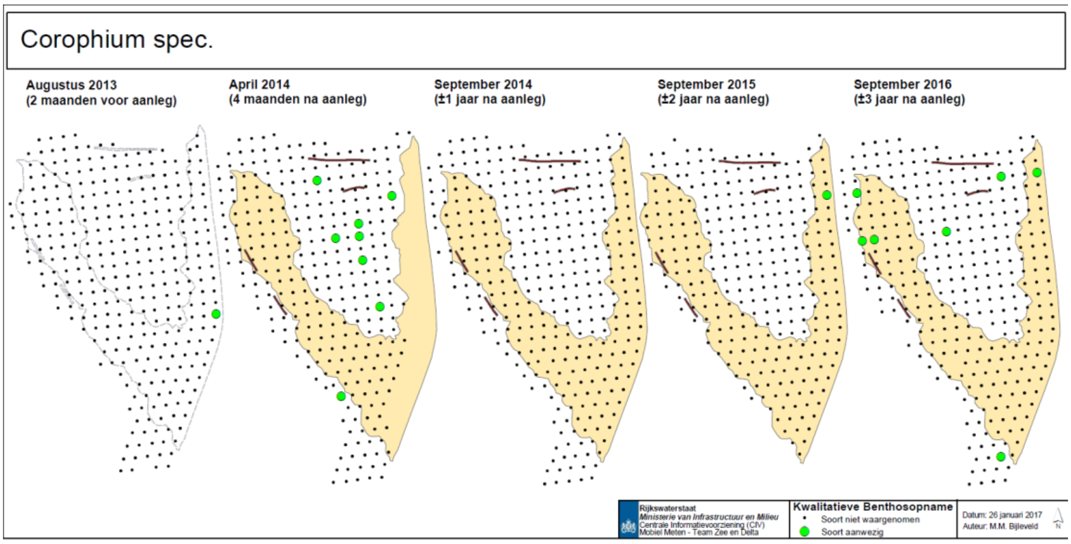
Corophium spec.
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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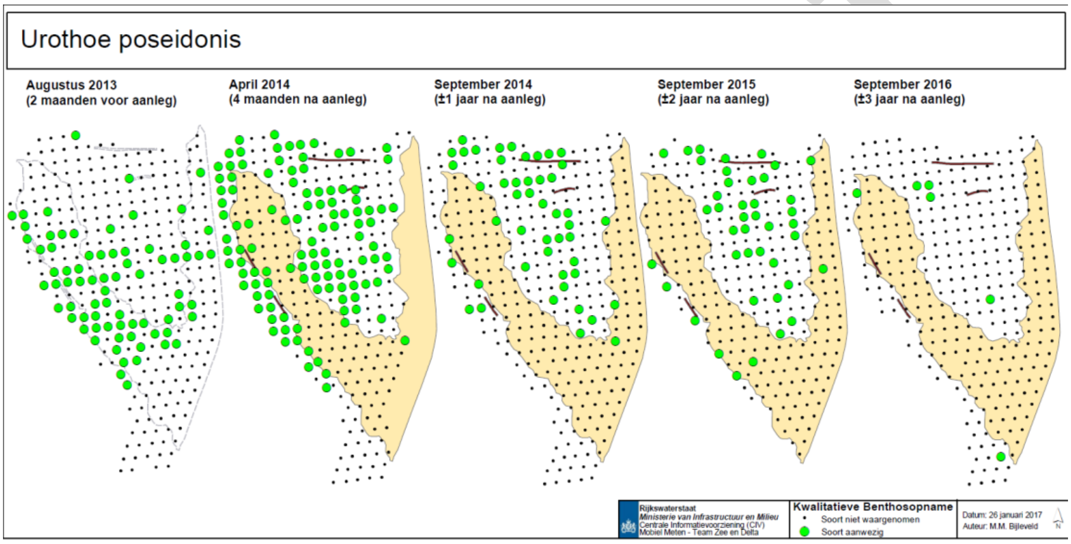
Urothoe poseidonis
Augustus 2013
(2 maanden voor aanleg)
April 2014
(4 maanden na aanleg)
September 2014
(±1 jaar na aanleg)
September 2015
(±2 jaar na aanleg)
September 2016
(±3 jaar na aanleg)
Rijkswaterstaat
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Appendix 5. Distribution maps of seagrass *Zostra noltii* observed in 2017 on the Oesterdam. Data from Dick de Jong and Marieke van Katwijk.