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An estimation of the effects of *Ensis directus* on the transport and burial of silt in the near-shore Dutch coastal zone of the North Sea

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ABSTRACT

This paper describes the distribution of the razor clam *Ensis directus* in the Dutch coastal zone with emphasis on its relation to sediment grainsize, in particular silt. The study includes a spatial survey along the coast of North Holland (Netherlands) and an in-situ experiment for the burial of silt. Densities of *E. directus* appeared highest close to the coast in the siltiest sediment, where also the highest body mass index values (BMI) were found suggesting the best conditions for growth. The largest specimens with the lowest BMI were found at the less silty, outermost off-shore stations.

In the shallow (10 m) zone a "lander" frame was deployed at the seabed containing ~100 pvc tubes filled with silt free sand that each hosted either a living *E. directus*, an empty shell, or bare sand. After three 3-weeks periods the silt content in the different tubes was determined and compared. The silt content around a living *E. directus* appeared 34% (spring) and 12% (autumn) higher than around an empty vertical shell, and 56% (spring) higher than in bare sand.

We discuss the different pathways along which silt is brought into subsurface sediment layers and speculate about the potential role of *E. directus* in the coastal sediment and silt dynamics. It is estimated that *E. directus* facilitates the (temporal) burial of up to 6 Mton of fine particles in the coastal zone annually. This equals up to 27% of the annual SPM transport along the Dutch coast and is between 45 and 85% of the annual influx into the western Wadden Sea.

The results show that the coastal *E. directus* population has a large impact on mass balance and behaviour of SPM, and on the ecological functioning of Dutch coastal and estuarine ecosystems.

1. Introduction

Presently the American razor clam *Ensis directus* is the most abundant bivalve species along the Dutch coast. This species which originates from the US east coast has rapidly spread along north western European coasts since it was first observed in the German Bight in 1979 (Von Cosel et al., 1982; Armonies, 2001; Severijns, 2002), and from where it migrated to other areas (Arias & Anadon, 2012, Severijns, 2002, Dauvin et al., 2007). *E. directus* prefers to live in dynamic sedimentary conditions mostly in mobile sands where it can rapidly retract itself deep into the sediment (Drew, 1907; Trueman, 1967). Annual surveys by Goudswaard et al. (2013) showed that this species is presently dominating the macrobenthic biomass in the Dutch coastal zone and that its local standing stock is substantially higher than estimates of total bivalve biomass prior to its appearance. There is some debate whether this newcomer outcompeted native species. Dannheim & Rumohr (2012) supposed that that was not the case because its preferred habitat of mobile sands with high current speeds (Dekker & Beukema, 2012) has never been fully occupied by native bivalves. Severijns (2002) furthermore argues that it is very unlikely that *E. directus* has outcompeted other *Ensis* species, since historical records suggest that latter were not very common along our coast. The other species were still found along the beaches even 10 years after *E. directus* had invaded Belgian waters.

Since *E. directus* invaded European waters it has become an ecologically important species in coastal waters. Fish and birds have started feeding on it (Tulp et al., 2010; Cadee, 2000; Wolf & Meininger, 2004) and densities have become so high that a commercial *Ensis* fishery has developed. Dense beds might support a higher diversity of associated macrofauna in response to associated changes in the silt and organic content (Armonies & Reise, 1999). Near the island of Sylt they found an increase of the silt and organic content in a dense *E. directus* bed which they ascribed to the local production of fine faecal material. Though winter storms removed this fine fraction from the surface, it was retained in deeper sediment layers at their Sylt station. Given the massive numbers of *E. directus* along the entire Dutch coast (Goudswaard et al., 2013) a similar entrainment of silt could possibly be a significant term in the budget of alongshore tidal transport of silt

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and other SPM (RIKZ, 2002). At the same time this stretch of coast is subject to erosion requiring continuous shoreface and beach nourishments for maintenance. In the period 2013–2016 roughly 28×10^6 m^3 sediment is supplied on the North-Holland coast consisting mainly of sand with a small admixture of silt, which adds to the turbid coastal "river" running north. If *E. directus* actively influences the burial of silt its dense coastal population might have a significant influence on the transport budget of this fine sediment fraction.

Quantitative data on the rate of silt entrainment by *E. directus* are lacking. This study aims to assess this rate and explores *Ensis*' relationship with sediment grainsize on a wider scale along the coast of North-Holland. We experimentally tested whether living *E. directus* is capable of changing the sedimentary characteristics of a sediment core under in-situ conditions in this shallow, dynamic coastal zone, and compared the sedimentary impact of alive individuals with that of empty shells and bare sand. The experiments were conducted in conjunction with a survey on spatial distributions of this species and associated sedimentary conditions in the coastal zone of North-Holland.

2. Methods

2.1. Coastal distribution Ensis directus

In June 2011 a synoptic sampling survey was conducted covering a large part of the coastal zone of North Holland. Median grain size is 222 μm with 5.1% silt. The area is characterized by a marked seasonal cycle in bottom water temperature and primary production. At the end of summer the highest temperature reaches 18 °C. The salinity varies between 26 PSU in winter-spring and 32 PSU in summer. Maximum current speeds vary over the neap-spring cycle between 70 and 120 cm s^{-1}. The most near shore area is characterized by the existence of a turbidity maximum zone (TMZ) (van der Hout et al., 2015). More details about the area can be found in van der Hout et al. (2016; this volume) and in Witbaard et al. (2015).

During the sampling campaign 12 boxcore samples were collected from each of 8 transects perpendicularly oriented to the coast. Each transect extended up to 6 km from the coast and the 12 sampling stations had a depth profile from 8 to 19 m. From each boxcore (diameter 30 cm) a 10 cm long, 35 mm diameter subcore was taken. This core was split in a 0–5 cm and a 5–10 cm layer which were separately analysed for grainsize composition. The freeze dried sediment sample was sieved over a 2 mm screen, homogenized and analysed on a Beckman Coulter LS 13 320. The size range of particles that could be measured was 0.4–2000 μm which excludes clay particles (i.e. particles <0.4 μm). Hence the fraction 0.4–63 μm is accordingly denominated as "silt" (Wentworth Class) in following paragraphs. Apart from freeze drying of the sediment samples, no other treatments (oxidizing/acidification) were performed. Since none of such pre-treatments were performed the particle size spectrum will not necessarily be similar to silt contents and grain size composition as reported by geologists which do apply such methods. Notably our sediment data will also be based on the organic material in the samples.

The rest of the boxcore content was sieved over a 1 mm screen and *E. directus* were sorted out. Shell length, width and height were measured with digital callipers to the nearest 0.1 mm. Shell width (thickness) and height were measured at the posterior side (siphon) of the shell. In case a shell was collected incompletely (i.e. mostly only the siphon side) shell length was estimated from the shell width and the relationship between shell width and length found for complete shells. The soft body tissues were removed and dried until constant weight at 60 °C. The weight of the dried bodies was determined after which the organic parts were incinerated at 540 °C for 4 h. The remaining material (ash) was weighed. Ash Free Dry Weight (AFDW) was subsequently calculated as the difference between dry weight and ash weight. AFDW and shell measurements were used to calculate the body mass index (BMI) or condition. Condition expresses the tissue weight per standard shell volume. Shell volume was calculated as shell length × shell height × shell width instead of shell length^3, since population data collected in 2011 and 2012 (Witbaard et al., 2015) showed that if length^3 was used, the body condition remained dependent of shell length. Hence the condition indices presented here differ from those reported by other authors like e.g. Dekker & Beukema (2012). The calculated condition indices were used to depict spatial patterns in the body condition, i.e. across and along shore. BMI and size (expressed as AFDW ind^{-1}) of *E. directus* in combination with environmental data (grainsize, depth, distance) were used in a redundancy analyses (R; Package Vegan; Oksanen et al., 2013) to identify which environmental factor could explain its distribution, size and condition in the study area.

2.2. Silt burial experiment

2.2.1. Experimental setup

In 2010 burial of silt by *E. directus* was investigated in-situ by deploying experimental trays mounted on a measurement platform ("lander") at a ~10 m deep site off the coast of Egmond (52°38.249′N 04°36.294′E, Fig. 2; Witbaard et al., 2015) within a dense *E. directus* population. The lander consists of a triangular aluminium frame (height × width: 2 × 2 m) with a series of ballast weights (total 500 kg) fixed onto its lowest horizontal structure. The platform was equipped with three mesocosm trays (97 ∗ 25 ∗ 16 cm, with the top side 54 cm above seabed). During the deployment periods each of the three mesocosms contained 36 PVC tubes with a diameter of 7 cm and a length of 15 cm. Each tube was filled with well sorted sand with a median grain size of ~314 μm and an average silt content of 0.12%. Within each mesocosm, three treatments, i.e. tubes with three different types of fillings, were tested. Half of the tubes carried a living *E. directus* of approximately 100 mm long. A quarter of the tubes contained an vertically positioned empty *E. directus* shell of the same length and the other quarter of the tubes were filled with sand only. Just before deployment of the lander the prepared tubes with the 3 different types of filling (treatments) were regularly distributed within and between each of the 3 mesocosm trays. At the time of deployment the mesocosms were closed with a hydraulically operated lid. The lid opened 1 h after deployment. At the end of the deployment period the hydraulic lids were closed again at a pre-set date and time. The closure of the lids prevented wash out of sediments from the tubes during deployment and recovery of the measurement platform.

The lander furthermore carried a series of instruments to monitor biotic and abiotic conditions at heights between 30 cm and 200 cm above the bottom. The instrument package comprised a current meter (speed-direction-pressure), a CTD (temperature, salinity) and several turbidity and fluorescence sensors. Detailed information about these measurements is given in Witbaard et al. (2013, 2015) and van der Hout et al. (Submitted).

In 2010, the platform was successfully deployed 3 times for a 3-weeks period i.e. twice in spring 2010 and once in autumn 2010 (Table 1). After recovery of the measurement platform from the seabed, the depth of the sediment surface below the top edge of each tube was measured. For the analyses only tubes were used from which the sediment surface was at maximum 1 cm below the top edge of the PVC tube. An a-priori selection of tubes was randomly made. In case a living *Ensis* in one of these selected tubes had died, the nearest tube with a living *Ensis* was selected. Tubes with a shell of which the animal had died during the deployment were not used. The specimen could have died shortly after the start of the deployment implying that the length over which the animal could have influenced silt distribution is unknown. The contents of the tubes were used in the grain size analyses following the procedure described in Section 2.1.

2.2.2. Spring experiments

In spring the lander was deployed during two periods (week 10–14 and week 14–17 (Table 1) of respectively 25 and 17 days. The contents

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