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In situ investigation of the effects of current velocity on sedimentary mussel bed stability

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ABSTRACT

The intertidal sediments of the Wadden Sea is an environment where organisms must endure significant physical stresses. Organisms like the blue mussel (*Mytilus edulis*), face the difficulty of maintaining their position in an unstable substrate. Previous studies on mussel beds in sediment showed that the substrates mussels use for attachment can differ across a bed. Increased adhesion to shell debris in the sediment resulted in what appeared to be a reinforced bed edge. To quantify the erosion resilience in different substrate use zones of an intertidal mussel bed, three distinct zones in a mussel bed were exposed, *in situ*, to artificially generated current velocities. Velocities ranged from high (0.7 m s^{-1}) to very high (1.43 m s^{-1}), covering the upper extremes of current velocities measured on mussel beds and those well beyond normal conditions. Silt content of the sediment was decreased 20% towards the bed edge. Results showed that the resilience of the mussel bed to erosion differed significantly between zones. The zone along the bed edge showed the greatest resilience to erosion remaining intact at current velocities of 1.43 m s^{-1}. This was also the zone with the greatest mussel cover (90%) and highest density. Erosion resilience was lower in the zones closer to the bed center. Erosion of mussels was always precluded by erosion of the sediment underlying the mussel bed (undercutting). In the zone with an intermediate mussel cover (77%), undercutting already occurred at a current velocity of 0.7 m s^{-1} and was twice as pronounced as in the site with the lowest mussel cover (53%). In all zones, mussel dislodgement did not occur below current velocities of 1.16 m s^{-1}. In zones towards the bed center, complete erosion of the bed occurred at 1.43 m s^{-1}. Results suggest that a 10% lower mussel coverage increased undercutting by 50%. The reinforced waveward bed edge proved to be capable of resisting erosive forces likely only exceeded during extreme storms. The presence of such a resilient barrier shields the rest of the bed from erosion allowing mussels in the sheltered zones to invest fewer resources in adhesion. Results show the significance of mussel coverage and adhesion on bed resilience. Any predictive modeling or artificial restoration efforts should account for and facilitate the development of such bed edges to improve a beds chance of survival.

1. Introduction

Many organisms thrive in the extreme environment on the intertidal benthic surfaces. Organisms living in this habitat are subjected to numerous stressors (Friedland and Denny, 1995; Tomanek and Helmuth, 2002) of which hydrodynamic stress resulting from wave action is most important (de Swart and Zimmerman, 2009; Donker et al., 2012; Moeser et al., 2006; Stephens and Bertness, 1991; Zardi et al., 2007). Sedentary organisms living in this environment must maintain a stable position on the benthic pelagic interface in order to successfully feed without getting dislodged and washed into an unsuitable site. The sedentary blue mussel *Mytilus edulis* makes use of byssus threads that it attaches to the substrate surface (Bairati and Vitellaro-Zuccarello, 1974; Bell and Gosline, 1996; Carrington et al., 2008; Meadows and Shand, 1989; Waite, 1992) in order to maintain its position. These elastic collagenous fibers themselves can possess surprising tensile strengths (Bell and Gosline, 1996; Price, 1980; Qin and Buehler, 2013). In rocky intertidal environments anchorage to a stable substrate is a relatively straightforward process. While it is true that most organisms in such environments seek sites of minimum stress to settle (Stephens and Bertness, 1991), the substrate they eventually anchor themselves to is inherently stable or has sufficient bulk to resist being washed away. In sediments, such as found on the back barrier tidal flats of the European Wadden Sea, the substrate available for attachment is unstable. Often the sediment particles used for adhesion consist of the dead shells of organisms formally living there (wa Kangeri et al., 2014). These particles are often no more resistant to

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erosion than the individual organisms themselves. Yet intertidal sediments around the world are populated by dense aggregations of mytilid mussels (Commito et al., 2014; McGrorty and Goss-Custard, 1991; Salas et al., 2015; Widdows et al., 2009).

The persistence of, in particular, *M. edulis* in the sedimentary environment has largely been attributed to their aggregative nature. Although such aggregation can have detrimental effects for the individual (Alunno-Bruscia et al., 2001; Bertness and Grosholz, 1985a), there are survivorship benefits. The increased collective mass of interconnected individuals enables mussel aggregations to better resist erosional forces (Bertness and Grosholz, 1985b). Additionally, in dense aggregations mussels effectively shelter one another from hydrodynamic forces (Carrington et al., 2008; Moeser et al., 2006). This dampening of hydrodynamic forces can also translate to the sediment between and below such an aggregation, limiting resuspension of the substrate. What is more, the presence of epifauna like *M. edulis* can form a cohesive barrier, physically protecting the underlying sediment, a phenomenon known as armoring (Widdows et al., 2002). Widdows et al., 2002 showed that the resilience of the overall structure and the underlying substrate was improved when mussel coverage was close to 100%. Any decrease in mussel cover would result in increased erosion of sediment between the mussels by scour effects in the gaps between mussels. In the same study, Widdows et al. (2002) showed that under experimental conditions mussel beds on sandy sediments were able to further increase erosion resistance by greater interaction with the substrate. In the Wadden Sea the sediment composition in a mussel bed can differ greatly. Hydrodynamic attenuation by mussels results in muddy bio-deposits building up under dense mussel aggregations (Donker, 2015; Flemming and Delafontaine, 1994). Such bio-deposits consist of fine grained mud and silt and are often covered in microphytobenthic mats. Both these characteristics can have significant effects of hydrodynamic scour. Thus in a heterogenous muddy mussel bed the mechanisms described by Widdows et al. (2002) may not apply in all areas of the bed.

Previously, wa Kangeri et al. (2014) showed that in intertidal *M. edulis* beds, mussels residing in more exposed areas of a bed (mainly bed edges) employ a substrate use strategy that involves attachment to shell debris embedded in the sediment (Debris type). Since mussels in exposed sites might be expected to be better adapted to resist erosion by dislodgement and/or undercutting, these substrate use zones might be expected to be associated with different erosion resistances. Understanding whether mussel adhesion strategies actually influence mussel bed resilience is key to understanding the implications of mussel adhesion in an eco-physiological context. If they do, any predictions made concerning mussel bed survival and/or development for purposes of conservation or management would do well to consider it.

Therefore, the goal of this study was to test if the different substrate use zones of a natural mussel bed in the sedimentary environment also differed in erosion resilience. Unlike previous work looking at the influence of mussels on sediment erosion, we aimed to ascertain whether mussel substrate use and the strength of adhesion was indicative of erosion resilience of the bed structure. To this end, an *In Situ* Erosion Flume (ISEF), loosely based on that used by Widdows et al. (1998) and Houwing and van Rijn (1998), was designed specifically for use in a mussel bed. The ISEF utilized here followed an open ended design in order to accommodate significantly higher current velocities than achieved by a closed system, allowing for erosion thresholds to be reached. The capacity of the bed to resist erosion was tested *in-situ* in three sites within the same bed. In each site the mussel bed was subjected to three current velocities ranging from high (0.7 m s^{-1}) to very high (1.43 m s^{-1}) in order to test upper erosion thresholds. Between site differences in mussel density, coverage, substrate composition and attachment strength allowed the role of these factors to be evaluated.

2. Methods

2.1. Location description and zone characterization

In July 2013, three zones in a well-studied mono-layered intertidal mussel bed in the Western part of the Dutch Wadden Sea were selected (Fig. 1). Zones were selected to represent the transition between substrate use zones as described by wa Kangeri et al. (2014). The zones selected for experimental testing included, the front edge (**Z1**), where mussels are most exposed to wave forcing and generate the greatest number of byssus attachments. These attachments were primarily anchored to coarse shell material (Debris type). The bed center (**Z3**) where exposure to waves is lower and mussels adhere to one another (LC type) with fewer byssal threads and a transitional zone between these zones (**Z2**). Each zone was visually distinct (see Supplements Fig. S1) and different in resistance to compression by trampling (see Supplements Fig. S2).

Characteristics of each zone were recorded prior to any experimental work. The topography of mussel bed in the study area was recorded using a dGPS device (TRIMBLE GNSS ROVER, see Fig. 1). In each zone a digital image was taken one meter above the sample area perpendicular to the surface (Canon D10, 180dpi). Image contrasts were manually adjusted to exaggerate differences between the mussel structure and bare sediment. The number of darker pixels (mussel) and total number of pixels was counted using the histogram function in Adobe Photoshop CS6. The proportion of mussel cover was then calculated. A single sample of 225 cm^2 was then taken and used to determine mussel density (ind. m^{-2}) and mean mussel length (apex-umbo mm). In addition, another 12 randomly selected mussels were sampled in the immediate vicinity to assess mean adhesion strength of each zone using a method similar to that described by Salas et al. (2015) based on methods described by Bell and Gosline (1997). The body condition index (CI) of each of the collected mussels was measured by separating flesh from shell and determining Ash Free Dry Weight (AFDW) of the flesh. CI was calculated as AFDW (mg) per unit volumetric length ($Length^3$) (van der Meer, 2006; wa Kangeri et al., 2014; Waser et al., 2016).

Within each selected zone, 3 sites were marked out for experimental runs. Each site was selected to differ in altitude by <2 cm. In each site selected an ISEF was used to expose a 0.03 m^2 area of mussel bed to one of 3 current velocities; **F1**: 0.7 (±0.2), **F2**: 1.16 (±0.3) and **F3**: 1.43 (±0.3) m s^{-1}. The test area and flume were submerged in sea water from the nearby gully prior to flume runs. This was achieved by creating a water bath using an open bottomed PVC box of 1 × 2 m embedded 20 cm into the mussel bed and sediment (Fig. 2C). Flume runs were then conducted with the flume fully submerged.

In each case the selected current velocity was gradually built up at a rate of 0.02 m s^{-1} s^{-1} and maintained for a total of five minutes. Following this, the water bath containing the flume was allowed to slowly drain completely before the flume box was removed and the test surface exposed for results to be observed and recorded. Only single runs were performed to allow the study to be conducted within one tidal cycle.

In each experimental site, a single sediment sample was taken using a 7 cm diameter tube with a coring depth of 10 cm (including the mussel layer). These sediment samples were freeze dried and weighed. Dried sediment was then sieved over a 5 and 2 mm sieve separating the sediment into 2 fractions; Fine Shell Debris (FSD) and Coarse Shell Debris (CSD). Each fraction was weighed in triplicate. Values were used to calculate the available mass of each fraction within the test area of the flume (300 cm^2).

2.2. Description and use of the In Situ Erosion Flume

A simplified open ended system was designed and built based on designs by Houwing and van Rijn (1998). The flume consisted of a 45 × 10 × 15 cm (internal L × W × H) box constructed of smooth concrete form plywood. The horizontal test surface consisted of an opening of