PLANT EFFECTS ON HYDRODYNAMICS AND SEDIMENTATION AT COASTAL WETLAND EDGES

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Coastal wetlands such as mangrove forests and salt marshes form the final terrestrial frontier facing the open sea. Wetlands attenuate wave energy, decelerate currents and affect turbulence, which can have profound implications for the morphological development of coastal wetlands such as coastal vegetation retreat or progradation. Offshore hydrodynamic forcing and mechanical (rigidity, buoyancy) and spatial (density) vegetation traits determine these processes. Using DHI's shallow water basin facility, we aimed to quantify how salt marsh and mangrove mimic vegetation attenuate wave and current energy, modify turbulent kinetic energy (TKE), and thus control sediment transport. These factors will determine wetland progradation rate or landward retreat. Combining densities of vegetation, mimic vegetation types (mangrove and salt marsh), waves and currents allows us to tease apart controlling factors of retreat and progradation in these environments. Sedimentation rates varied across mangrove and salt marsh vegetation, hydrodynamic conditions and densities. When only waves were deployed, both vegetation types showed accumulation of sediment, but for mangroves this was only at the patch front. The addition of currents did not change accumulation patterns for salt marshes but it did indicate erosion at the front of the mangrove mimic patch. Reducing mimic density caused erosion in both mimic patches, with salt marsh mimics characterised by erosion at the patch back whilst for mangroves erosion localised in the patch middle. The wave height decay observed along the two vegetation types relates to the accretion patterns observed within the meadow compared to the open channel. The erosion observed in both patches when their density was reduced is linked to an increase of TKE inside the meadow when it is sparser. Our results complement recent work by obtaining a better understanding of wave-current flow features at vegetation edges expanding our understanding of coastal wetland dynamics, and providing information used to increase coastal resilience and therefore protection.

1. INRODUCTION

Coastal ecosystem engineering dominated wetlands, i.e. mangrove forests and salt marshes, form the final terrestrial frontier facing the open sea. As such, they provide important ecosystem services for coastal protection by trapping sediments, attenuating waves and slowing currents (Moeller et al., 2014; Quartel et al., 2007; Temmerman et al., 2013). Together with their ability to adapt to sea-level rise through aggradation (vertical growth) and progradation (horizontal, seaward growth) [4], their ability to provide these services has led to increased interest in the use of coastal wetlands for defence against coastal flooding and tsunamis.

Despite this interest, little is known about the dynamics of coastal wetland progradation (and retreat), particularly under the effect of combined waves and currents [5-8]. The position of a wetland's seaward edge (Figure 1) is determined by the plants' tolerance to inundation and mechanical stresses, and sediment re-distribution caused by the hydrodynamic forces impacting upon them. Landward retreat is initiated by sediment erosion or drowning of ecosystem engineering plants (Morris et al., 2002), whereas progradation occurs when the tidal flat accretes to a height that is colonisable, or the physical conditions temporarily allow new vegetation establishment (Balke et al., 2014a; Balke et al., 2015). To understand progradation further information is required on wetland edge processes (Balke et al., 2013; Balke et al., 2014b) to enable managers to predict the progradation of coastal wetlands and thus use them to protect coastlines and infrastructures.

Figure 1 The seaward edge of A) *Rhizophora* mangrove forest, B) *Spartina* salt marsh.

Vegetation attenuates wave energy, decelerates currents and affects turbulence such that eddy length scales become dominantly governed by plant wake characteristics, rather than by the bed boundary layer (Nepf, 1999). For example, the quasi-discontinuous edges of *Spartina* salt marshes (Figure 1B) induce a sharp transition in hydrodynamic energy, potentially leading to cliff formation, whereas the transition at the seaward interface of mangrove forests is smoother, due to their lower density per surface area (Figure 1A). In general, the nature of this transition is determined by a) the offshore hydrodynamic forcing; and b) the mechanical (rigidity, buoyancy) and spatial (height, density) traits of the ecosystem engineers and can have profound implications for the morphological development of coastal wetlands.

In these experiments, we aim to quantify the way in which contrasting ecosystem engineers i.e. salt marsh and mangrove forest vegetation, attenuate incident wave and current energy, modify the nature of the turbulent kinetic energy (TKE), and thus control the sediment transport which determines the rate of progradation or landward retreat. Our results will complement recent work (Losada et al., 2016; Maza et al., 2013; Maza et al., 2016) in order to obtain a better understanding of wave-current flow features at vegetation edges. They will increase our understanding of coastal wetland dynamics, and deliver information that could be used for efforts to increase coastal resilience and therefore protection.

2. METHADHOLOGY

The flume experiment was completed using two different ecosystem-engineering mimics: *Spartina* – a common pioneer plant found at the seaward edge of salt marshes, and *Rhizophora* roots – a common fringing mangrove. Each mimic patch was composed of 12.25 m^2 (10 m in length and 1.25 m in width; Figure 2) plywood sheets upon which the different mimics were attached.

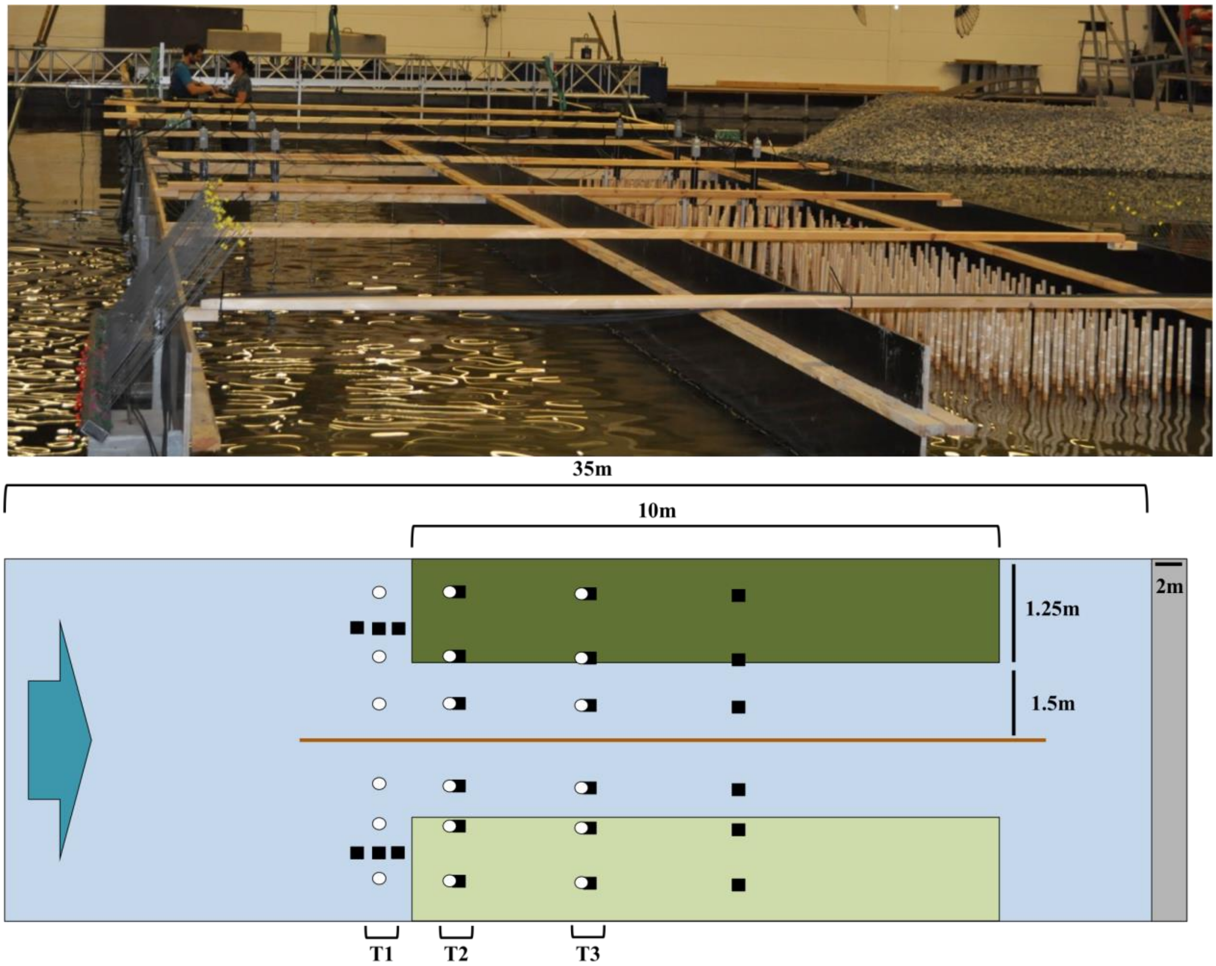

Figure 2. The top picture shows the flume in operation with mangrove mimics on the right hand side and saltmarsh mimics on the left hand side (not seen because of water depth). The bottom section shows a conceptualised experimental setup (not to scale). Depicting the set-up of the *Spartina* mimic patch (light green panel) and *Rhizophora* mimic patch (dark green panel) from an aerial perspective. White dots indicate the placement of the ADVs, which were fixed onto a traverse that moved down the flume. The black squares represent wave gauges, which were fixed in position. The large blue arrow indicates the wave and current maker. The grey patch indicates the beach to absorb waves and reduce reflection. The brown line is the wall between the two vegetation patches and the channel. The ADV's were placed at -0.75, 0.5, 2.0 m along the flume and at 0.75, 1.25 and 2.0 m across the flume. Whilst wave gauges were placed at -0.75, 0.5, 2.0 and 5.0 m along the flume and at 0.75, 1.25 and 2.0 m across the flume. T1 represents transect 1, T2 is transect 2 and T3 transect 3.

The *Rhizophora* root mimics were constructed using pine poles (0.03 m in diameter**,** 0.7 m long), and were pushed into holes in the plywood until the pine reached the concrete floor (Figure 3B). *Spartina* mimics were mimicked with straightened plastic tubing **(**0.006 m in diameter**,** 0.5 m long**),** which were pushed onto a nail (0.2 m) in the plywood (0.2 m of the *Spartina* mimics were buried in the sediment) (Figure 3A).

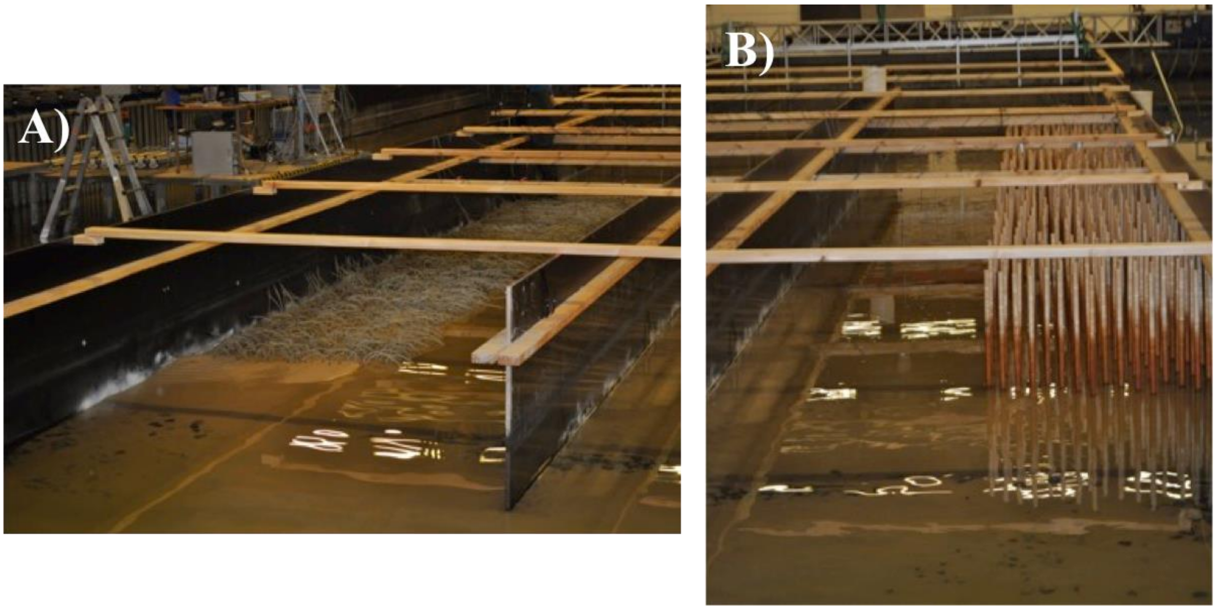

Figure 3. Showing salt marsh mimics on the left hand side (A) and mangrove mimics on the right hand side (B).

After mimics had been fixed, sediment (non-cohesive, 0.18 mm) to a height of 0.2 m was placed into the flume. In both cases, we had two separate patches of the same vegetation on either side of the flume with a wall and a 5 m dividing channel between them, so that the configuration covered the entire width of the flume (Figure 2).

To measure the hydrodynamics, we deployed 6 Acoustic Doppler Velocimeters (ADVs) across the flume, 3 on the *Rhizophora* mimic side and 3 on the *Spartina* mimic side (Figure 2). Waves were measured with fixed conductive wave gauges (Figure 4).

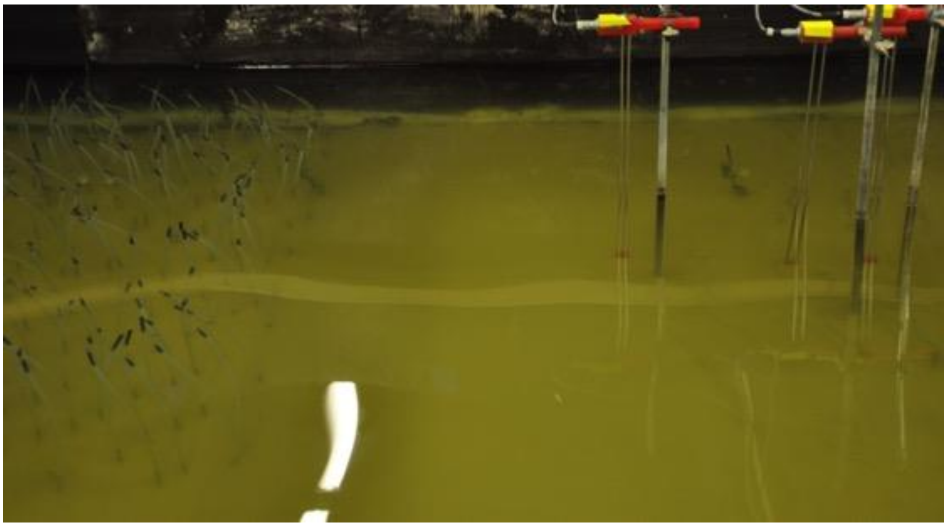

Figure 4. Showing the three waves gauges (right hand side) at the front of the salt marsh patch (left hand side).

The ADV's measured velocity profiles acquiring points every 5 cm in the vertical, except in the second transect where points every 2 cm were recorded. Surface elevation change at in the vegetation patches was measured using sedimentation erosion bars (SEBs), with elevation measurements at 5-10 cm intervals using metal pins lowered through the bar. The bars were moved along the flume taking measurements at -0.75, -0.1, 0.1, 0.5, 1.5, 2.5, 5, 7.5, 10 and 10.75 m. Behind the vegetation a perforated sloping beach was located, so that the waves were not reflected back into the vegetation patches but the flow was maintained. After each hydrodynamic condition, the bathymetries of the vegetation patches were measured using the SEBs and then the sediment re-levelled. When we changed the density the flume was emptied, and half the mimics were taken from each vegetation patch. Runs were carried out using two different densities of each vegetation (*Rhizophora* roots low 42 roots m^{-2}, high 84 roots m^{-2} and *Spartina* stems low 210 plants m^{-2}, high 420 plants m^{-2}). We applied waves (H = 0.08 m and T = 0.8, 1.1, 1.4 s), currents (v = 0.3 ms^{-1}) and combined waves and currents (H=0.08 m, T= 0.8, 1.1, 1.4 s, v=0.3 ms^{-1}). We investigated current-only and waves-with-currents (in flood tide settings i.e. waves and currents propagating in the same direction) conditions, as in previous studies (Anderson and Smith, 2014; Hu et al., 2014; Jadhav et al., 2013). All these flow conditions were tested over a water depth equal to 0.30 m resulting in submerged (*Spartina* mimics) and emergent (*Rhizophora* mimics) vegetation conditions.

3. RESULTS AND DISCUSSION

Wave height evolutions along the two vegetation meadows were analysed. 50 waves were considered in the analysis and mean wave height was obtained. Figure 5 shows results for two wave conditions: H = 0.08 m and T = 0.8 and 1.1 s. Wave height values are divided by the incident wave height measured at 0.5 m offshore the meadow. Figure 5 shows a higher attenuation along the first 2 m for the mimic mangroves than for the saltmarshes.

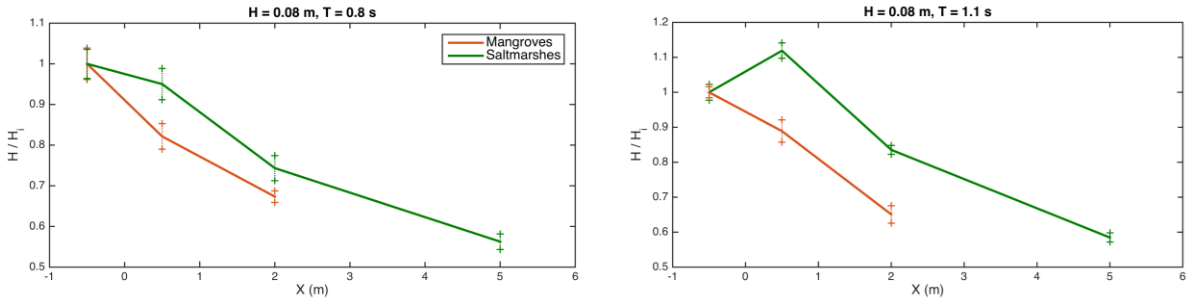

Figure 5. Wave height evolution along the mangrove (brown) and saltmarshes (green) meadow for two wave conditions: H = 0.08 m, T = 0.8 s and H = 0.08 m, T = 1.1 s. X = 0 shows the beginning of the meadows. Mean wave height values divided by the incident wave height (H_i) for 50 waves are displayed and standard deviation are shown in dotted lines.

Waves (H=0.08 m, T=1.1 s) showed sediment accumulation (≈2-4.5 cm) in the mimic *Spartina* patch at high densities. Whilst for mimic *Rhizophora* roots, sediment accumulation was only measured at the front of the patch, the remaining patch showed little or no change from the initial bed level. Previous research has found that shoot stiffness was the most significant plant trait involved in wave attenuation (Bouma et al., 2005). The sediment patterns and wave gauges agreed with this. The stiffer *Rhizophora* mimics significantly reduced attenuated wave height at the front of the patch causing sudden sediment deposition, whilst *Spartina* plants gradually attenuated wave height thus allowing for deposition through the entire patch.

When we combined currents (v=0.3 ms^{-1}) with waves (H=0.08 m, T=1.1 s), sediment movement was greater in both mimic *Rhizophora* roots and *Spartina* plants. *Spartina* plants in the initial patch edge showed erosion, but the majority of the patch showed accumulation (≈ 2-5.5 cm). *Rhizophora* mimics had widespread erosion across the entire patch and showed only two areas of accumulation, one at 2.5 m and the other at the 10 m point on the channel side. These points also were a hotspot for the *Spartina* mimic patch, which also showed accumulation at this point. Flexible canopies such as *Spartina* are more efficient at reducing erosion by reconfiguring their leaves with combined waves and currents (Peralta et al., 2008) so deflecting the flow, whilst the mimic roots had greater flow through. The greater erosion in the channel of the *Spartina* mimics also indicates higher lateral flow deflection from the *Spartina* mimics compared to the *Rhizophora* root mimics, which had lower channel erosion. For salt marsh plants, increased sedimentation allows for the lateral expansion of their populations (Peralta et al., 2008).

When reducing the density of the plants and roots, we found that *Spartina* mimics again showed higher accumulation and lower erosion compared to *Rhizophora* root mimics, with combined waves and currents. Indicating that even at lower densities salt marsh plants accumulate more sediment and reduce greater erosion compared to *Rhizophora* roots. Although there was greater erosion within the *Spartina* patches compared to higher densities, this could be because lower density plants can sway within the water column causing turbulence thus increasing sediment erosion (Bouma et al., 2007). Additionally, higher salt marsh densities can cause skimming flows as described above, where flow is deflected around the patch. Occurrence of skimming flow protects sediments from erosion, by lifting the boundary layer and displacing the high Reynolds stresses to areas higher up in the water column (Bouma et al., 2007).

Interesting for low and high densities with combined waves and currents, an eroded area at the front of the patch can clearly be seen. *Rhizophora* root mimics showed higher levels of erosion (>10cm) compared to *Spartina* mimics (>5cm). Additionally, *Spartina* mimics showed a distinct edge of erosion whilst *Rhizophora* root mimics show a much more graduated erosion edge. The higher erosion in the *Rhizophora* is because the roots extend through the entire water column whilst the *Spartina* plants were deflected by the flow covering only part of the water column, and there is a higher density of stems in *Spartina* mimics than the *Rhizophora* mimics. The eroded sediment in both patches are trapped within the vegetation patches, as it can be seen that accumulation beyond the eroded patches is still high.

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