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# Unravelling the controls of lateral expansion and elevation change of pioneer tidal marshes

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ABSTRACT

Many overlapping mechanisms have been proposed to control horizontal seaward expansion of marshes and rates of elevation change that are associated with it. Key questions to resolve are: i) whether simple geomorphological conditions such as elevation are a reliable predictor of marsh expansion rates; ii) whether there are seasonal vegetation-induced effects on elevation change (both, increase and decrease of elevation); and iii) how steep the spatial gradient of elevation change is from the bare tidal flat into the vegetated marsh? These questions have been addressed with a two-scale study approach performed on two contrastingly wave-exposed marshes in the Scheldt Estuary (SW Netherlands and N Belgium) where *Scirpus maritimus* is the dominant pioneer species. On the one hand, we investigated the relations between large-scale, geomorphological parameters (elevation, slope) and clonal marsh expansion rates at both sites. On the other hand, we performed a small-scale monthly field monitoring over two years at the same two marshes where we investigated the relations between spatio-temporal variations in vertical elevation change and spatio-temporal variations in vegetation properties along cross-shore transects. We found that at the sheltered site, clonal expansion rates are almost twice as high as at the exposed site. Furthermore, expansion rates at the sheltered site related well to elevation. At the exposed site, this relation was less strong as wave exposure might cause a dominant disturbance. Moreover, we found clear seasonal elevation change patterns that closely followed the seasonal vegetation cycle, with prevailing increase in elevation in summer when above-ground biomass was maximal and decrease in elevation in winter when plant shoots had largely decayed. Especially at the exposed site, the presence of vegetation has a positive effect on increase in elevation within the marsh. Finally, our results show that clonal marsh expansion succeeded at elevations for which previous studies at the same locations showed that individual shoots could not establish, emphasising the importance of clonal integration for both survival and lateral expansion in disturbance-driven ecosystems.



## 1. Introduction

Tidal marshes provide many ecosystem services, ranging from natural habitat for specialized fauna and flora, to $CO_2$ sequestration, recreation and coastal protection (e.g. Barbier et al., 2011; Costanza et al., 2014; Möller et al., 2014). Given the increasing worldwide loss of tidal marshes over the last decades (e.g. Barbier et al., 2008; Kirwan and Megonigal, 2013), understanding the mechanisms determining horizontal seaward marsh expansion or landward retreat has gained importance. While vertical evolution of marshes has been well studied and extensively modelled, the mechanisms triggering horizontal expansion or retreat are still poorly understood (see review by e.g. Fagherazzi et al., 2012). For instance, a marsh can be vertically accreting while, at the same time, the marsh edge is horizontally retreating (Van der Wal et al., 2008). This illustrates to what point the two mechanisms – vertical versus horizontal evolution – are not necessarily coupled (Fagherazzi et al., 2013).

Horizontal expansion of marshes onto adjacent bare tidal flats can occur through two different mechanisms. On the one hand (1), individual plants can establish. This can happen when seeds disperse, deposit and germinate, or when pieces of rhizomes that become detached from the marsh settle on the mudflat. Marsh expansion by individual plant establishment typically succeeds in the presence of so-called windows of opportunity (Wiehe, 1935; Mateos-Naranjo et al., 2008; Balke et al., 2011 for mangroves), which are periods without disturbances that are long enough for plants to establish and to outgrow a critical biomass level (i.e. a critical root length) at which they can survive subsequent disturbance events (van Wesenbeeck et al., 2008; Balke et al., 2011, 2013 for mangroves; Hu et al., 2015). Disturbances and environmental stressors potentially limiting successful plant establishment in tidal systems are caused for instance by cyclic tidal inundation, storm

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surges, currents and waves, and the erosion caused by these water movements. On the other hand (2), the mudflat can also be colonized by lateral clonal propagation of the marsh edge: many perennial marsh plants can reproduce clonally, i.e. produce new shoots from the existing or expanding root system. By lateral below-ground expansion of rhizomes and growth of new above-ground shoots from these rhizomes, the entire marsh edge can advance onto the adjacent tidal flat. These pioneer shoots are connected to the existing marsh through their roots, which has an advantage compared to individually established shoots or seedlings: if they are connected to a sufficiently large patch or marsh they benefit from clonal integration (e.g. Bertness and Hacker, 1994; Amsberry et al., 2000; Burdick and Konisky, 2003). This means that shoots that are clonally connected to each other can avoid local physical and biological stresses by accessing distant resources. Through clonal integration shoots can then establish and survive in conditions (e.g. critical inundation depth, exposure to waves or currents, sulphide or salinity stress) in which individual shoots or seedlings – which do not benefit from clonal integration – cannot survive.

Colonization of bare intertidal mudflats by either of the two colonization strategies is known to be related to elevation relative to mean sea level or mean high water (MHW) as this is directly related to hydroperiod (e.g. Wiehe, 1935; Burdick and Konisky, 2003; Cox et al., 2003; Mateos-Naranjo et al., 2008; Wang and Temmerman, 2013). Longer hydroperiod linked to lower elevation leads, as direct effect, to higher inundation stress on the plants, and has furthermore indirect consequences such as a longer exposure to wave action or tidal currents. This, in turn, can then lead to higher risks of erosion of the sediment bed and to higher drag forces acting on the plants. These two mechanisms – erosion and drag forces on shoots – can, separately or in combination, potentially prevent plant establishment or provoke uprooting of established plants (e.g. Bouma et al., 2009a; Friess et al., 2012; Balke et al., 2013 for mangroves; Silinski et al., 2015a).

The presence of once established vegetation triggers positive feedbacks between vegetation and increase in elevation: the vegetation will reduce flow velocities and attenuate waves, which promotes increased sedimentation within the vegetation; this enhances surface elevation within the vegetation, which, in turn, creates better growing conditions for the vegetation as it is exposed to less and less tidal inundation, etc. (e.g. Redfield, 1972; Morris et al., 2002; Bouma et al., 2009b; Balke et al., 2014). It is thus generally expected that sedimentation prevails within the marsh due to the flow and wave attenuating effects of the continuous vegetation cover. Furthermore, also the plants themselves can add to an increase in elevation by root production (Morris et al., 2002; Kirwan and Guntenspergen, 2012) and marshes in sediment poor estuaries such as in New England (USA) are known to have grown up with sea-level rise over millennia due to peat accretion, i.e. accretion of (self-produced) organic material (Redfield, 1965; Kirwan and Guntenspergen, 2012). In contrast, these positive feedback mechanisms are absent on the mudflat, except possibly during spring when biofilms can temporarily stabilize the bare sediment (Paterson, 1989; Le Hir et al., 2007; Rietkerk and van de Koppel, 2008; Marani et al., 2010). Over the long term, this would imply that surface elevation increases in the marsh, while only small net surface changes occur on the dynamic mudflat. In certain situations, however, large sediment supply, elevation and local hydrodynamics may result in higher elevation increase on the low-lying bare tidal flat than within the high-lying vegetated marsh, inundation time being here the driving factor for sedimentation and increase in elevation (e.g. Cahoon et al., 2011).

While establishment of individual plants on bare mudflats has been investigated in a series of flume studies and field experiments (Mateos-Naranjo et al., 2008; van Wesenbeeck et al., 2008; Xiao et al., 2010; Balke et al., 2011 for mangroves; Zhu et al., 2014; Silinski et al., 2015a; Silinski et al., 2015b), detailed field studies on horizontal clonal marsh front expansion and its interactions with vertical elevation change in the expanding pioneer marsh zone are still lacking, despite its potential overriding importance for determining the marsh range (Callaghan et al., 2010). The aim of this paper is to elucidate bio-geomorphic processes influencing horizontal seaward expansion and vertical elevation change of pioneer marshes. We study this using the Scheldt Estuary (SW Netherlands and N Belgium) as model, where *Scirpus maritimus* L. Palla is the dominant pioneer species. Three main questions are addressed: (1) can rates of horizontal, seaward clonal expansion of pioneer marshes be explained by simple geomorphological parameters (elevation at the marsh edge, affecting hydroperiod; slope of the mudflat, affecting transformation of approaching waves and hence affecting wave exposure at the marsh edge) be used as proxy for predicting rates of horizontal, seaward clonal marsh expansion; (2) can rates of vertical elevation change within pioneer marshes be explained by temporal (seasonal) variations in plant properties; and (3) how steep is the spatial gradient in rates of vertical elevation change in the transition zone from bare tidal flat to vegetated pioneer marsh? A two-scale study approach was used to answer these questions: on the one hand, we investigated the relations between large-scale, geomorphological parameters and clonal marsh expansion rates at a wave-sheltered and wave-exposed site; on the other hand, we performed small-scale field measurements with a high spatial (meters) and temporal (monthly) resolution on the relations between spatio-temporal variations in vertical elevation change and spatio-temporal variations in vegetation properties (shoot density and height) along cross-shore transects at the same two pioneer marshes.

## 2. Materials and methods

### 2.1. Study sites

Two neighbouring marshes were monitored in the brackish part of the macrotidal Scheldt Estuary: the marsh of Rilland (SW Netherlands) and Groot Buitenschoor (N Belgium) (Fig. 1). These two marshes have each an alongshore length of approximately 3.5 km. By choosing these, we followed a disturbance gradient from wave-exposed marshes at the Dutch site (in the following referred to as exposed site) towards more wave-sheltered marshes at the Belgian site (in the following referred to as sheltered site). For example, significant wave heights ($H_{1/3}$) recorded for one location at both sites during the growing season of 2014 were 5.7 cm and 2.8 cm for exposed and sheltered site, respectively, and the mean of the highest percentile ($H_{1/100}$) were 20.3 cm and 9.7 cm (own measurements). These values were calculated for all wave data gathered during tidal inundation at both marsh edges. These differing conditions arise from two compounding effects (Fig. 1c): (1) the wind fetch of dominant south-western winds is shorter at the sheltered site (8 km versus 2 km for exposed and sheltered site, respectively); and (2), a breakwater protects the sheltered site from direct wave impact from both ship and wind waves, while the shipping channel passes very closely by the seaward limit of the tidal flat at the exposed site. Most parts of these marshes are characterized by a gently sloping marsh-mudflat transition zone, indicative of seaward expansion of the marshes. The sediment surface of the sheltered site consists mainly of silty sediment (>65% silt in the top 5 cm layer), while the sediment surface of the exposed site is mainly sandy (on average > 85% sand in the top 5 cm layer). Annual averaged suspended sediment content in the area is $62 \pm 4.3$ SE mg $L^{-1}$ (Maris et al., 2013) and the average tidal range is 5 m. At both sites, *Scirpus maritimus* L. Palla is the dominant marsh pioneer. While it has been reported that the marshes in the Scheldt experienced alternating phases of expansion and retreat over the last century (e.g. Cox et al., 2003; Van der Wal et al., 2008), a continuous clonal expansion over large alongshore stretches of the two studied marshes has been observed over the period of 2006–2014 (personal communication by Hug van Beek and own observations since 2010).