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Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing

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Abstract

Salt marshes deliver vital ecosystem services by providing habitats, storing pollutants and atmospheric carbon, and reducing flood and erosion risk in the coastal hinterland. Net losses in salt marsh area, both modelled globally and measured regionally, are therefore of concern. Amongst other controls, the persistence of salt marshes in any one location depends on the ability of their substrates to resist hydrodynamic forcing at the marsh front, along creek margins and on the vegetated surface. Where relative sea-level is rising, marsh elevation must keep pace with sea-level rise and landward expansion may be required to compensate for areal loss at exposed margins. This paper reviews current understanding of marsh substrate resistance to the near-instantaneous (seconds to hours) forcing induced by hydrodynamic processes. It outlines how variability in substrate properties may affect marsh substrate stability, explores current understanding of the interactions between substrate properties and erosion processes and how the cumulative impact of these interactions may affect marsh stability over annual to decadal timescales.

Whilst important advances have been made in understanding how specific soil properties affect near-instantaneous marsh substrate stability, less is known about how these properties interact and alter bulk substrate resistance to hydrodynamic forcing. Future research requires a more systematic approach to quantifying biological and sedimentological marsh substrate properties. These properties must then be linked to specific observable erosion processes, particularly at the marsh front and along creek banks. A better understanding of the intrinsic dynamics and processes acting on, and within, salt marsh substrates, will facilitate improved prediction of marsh evolution under future hydrodynamic forcing scenarios. Notwithstanding the additional

complications that arise from morphodynamic feedbacks, this would allow us to more accurately model the future potential protection from flooding and erosion afforded by marshes, while also increasing the effectiveness of salt marsh restoration and re-creation schemes.

Keywords: Salt marsh stability; Erosion; Substrate Properties; Process-based measurements; Nature-based coastal protection

1. Introduction

1.1. The importance of marsh stability

Salt marshes are globally-distributed, intertidal wetlands, occupying distinct elevation ranges that vary depending on tidal regime (Fig. 1; Friess et al., 2012). In NW Europe, for example, they are generally found at elevations between the mean high water neap tide and highest astronomical tide levels (Adam, 2002; Balke et al., 2016). On the East coast of the USA, they can be found below mean sea level, through to the highest astronomical tide level (Fig. 1). However, as salt marshes in North West Europe often experience a larger tidal range than those on the US East Coast, their vertical elevation range can exceed that of marshes on the microtidal US East coast. The frequency with which marshes are inundated by salt water and thus affected by shallow water coastal processes depends on their position within the tidal frame, and also meteorological forcing (Steel, 1996). Salt marshes typically comprise fine-grained sediment (Dronkers, 2005) colonised by halophytic vegetation, once a given elevation is reached (Allen, 2000; Huckle et al., 2004). [Insert Figure (1) here]

The existence of salt marsh landforms is of high societal importance as their associated ecosystems provide important regulating, provisioning and cultural ecosystem services (Boorman, 1999; Barbier et al., 2011; Foster et al., 2013; Spalding et al., 2014). These include carbon sequestration (Rogers et al., 2019), habitat provision (Spencer & Harvey, 2012) and pollutant immobilisation (Crooks et al., 2011). Salt marshes have an elevated position in the tidal frame and high surface roughness due to micro-topographic variability and the presence of a vegetation canopy; in addition, these surfaces may be dissected by bifurcating channel networks. When flooded, salt marshes are therefore efficient dissipaters of incident wave energy, including under storm surge conditions (Loder et al., 2009; Möller et al., 2014; Möller & Christie, 2018). This dissipation is an integral morphodynamic feedback, with co-adjustment of process and form (Fig. 2), facilitating landform persistence. Such morphodynamic feedbacks occur when the biota and hydrodynamics influence each other through both lagged and instantaneous responses, which often exaggerate the effect of a given change and the resultant effect on the salt marsh landform. As marsh surfaces also store floodwaters, these feedbacks also lower the risk of coastal flooding and erosion (and thus the societal cost associated with these processes) landward of the landform (Beaumont et al., 2008; Pollard et al., 2018). [Insert Figure (2) here]

Spalding et al. (2014) recognise that marshes can provide significant advantages over conventional hard engineering approaches in particular locations. This is both because of the range of ecosystem services they provide and also because, with sufficient sediment supply, biophysical feedback mechanisms (see Kirwan et al., 2016; Schuerch et al., 2018) allow marshes to accrete vertically (and in some cases laterally) in response to environmental forcing (e.g. accelerated sea level rise). As such, marshes can sustain their position in the tidal frame. As a result, Vuik et al. (2019) used a probabilistic modelling approach and found that, over 100 year timescales, incorporating vegetated intertidal foreshores into flood protection schemes can be more cost-effective than simply raising/reinforcing fixed position sea walls/levees.

Given the importance of salt marshes, marsh margin retreat and internal marsh dissection through erosion of cliffs and creek banks is a topic of concern. Margin retreat and internal dissection have been recorded on many of the world's shores (Cooper et al., 2001; van der Wal & Pye, 2004; Baily & Pearson, 2007; Crooks et al., 2011), and replicated in modelling studies (e.g. Blankespoor et al., 2014). Reports of marsh margin retreat vary from less than a few centimetres per year at, for example, certain locations in the eastern USA (Leonardi & Fagherazzi, 2014; 2015) to more than 10 metres per year, as reported, for example, for locations in the outer Thames estuary (Greensmith & Tucker, 1965). Marsh margin retreat rates therefore appear to be highly site-specific.

Long-term marsh cliff retreat rates have been correlated to average wave power at the cliff and has been shown to follow both linear (Marani et al., 2011; Priestas et al., 2015; Leonardi et al., 2016; Finotello et al., *in press*) and power-law trends (Schwimmer, 2001; Mariotti & Fagherazzi, 2010). The precise relation between wave power and erosion rate is site-dependent and likely varies with local biological, geochemical and sedimentological properties, marsh morphology and marsh elevation relative to tidal water levels (McLoughlin, 2010; Tonelli et al., 2010; Leonardi & Fagherazzi, 2015; Priestas et al., 2015).

Questions thus arise as to the processes causing marsh erosion, not least regarding the potential existence of hydrodynamic forcing thresholds, i.e. wave/tide-generated forces that, when exceeded, cause the near-instantaneous removal of sediment and/or plants from the marsh surface or fringe. Once consolidated, the horizontal marsh surface has been shown to be relatively resistant, for example to wave action (Spencer et al., 2015a). This is in contrast to reported examples of marsh margin erosion and evidence linking this erosion to hydrodynamic forcing (e.g. Schwimmer, 2001; McLoughlin et al., 2015). A number of studies have thus attempted to better understand what makes marsh substrates (the minerogenic and organic components of the bulk marsh material) resistant to erosion by the action of water. This paper reviews these studies in search of overriding properties affecting marsh substrate behaviour under the action of water, how these interact and how these may affect the dynamics of exposed substrates on the surface, creek banks and at the marsh edge. This paper explores what these existing studies reveal about longer term (annual to decadal scale) trajectories of marsh loss, bearing in mind that morphodynamic feedbacks play a key role in moderating future force-response relationships. Finally, this paper identifies areas for future research, which could ultimately improve both modelling of future marsh extent in response to various forcing scenarios and also the efficacy of management schemes (either for marsh restoration or creation).

1.2. Marsh soil formation and stability

Salt marsh formation is a function of net sediment accumulation under low-energy conditions. Over time, dewatering and compaction lead to the formation of a 3-D sedimentary body, the characteristics of which reflect the allochthonous (externally-derived) and autochthonous (internally produced, organic) sediment contribution (Allen, 2000). On natural salt marshes, landscape-scale change is largely driven by accommodation space, sediment availability and type (source) alongside variations in sea level (Spencer et al., 2016; Schuerch et al., 2018). The composition of marsh substrates reflects a wide range of factors, including geological setting, tidal setting, climatological influence, and anthropogenic intervention / land-use regime (Crooks & Pye, 2000; Schuerch et al., 2016).

Once formed, the marsh platform has been shown to be remarkably resistant to wave-driven erosion (Steers, 1953; Steers et al., 1979; Spencer et al., 2015a; Spencer et al. 2015b). Marsh erosion occurs mainly from the marsh edge, where incident wave energy is highest, and can result in lateral retreat. Such erosion occurs if resisting forces (structural, biological, frictional and cohesive substrate strength) are exceeded by eroding forces (e.g. hydrodynamic forcing). This paper therefore refers to 'marsh substrate stability' as the ability of the marsh substrates exposed horizontally at the surface or vertically and sub-vertically at exposed marsh edges, to resist the near-instantaneous erosive force of water generated, for example, by waves (Fig. 3). In doing so, this paper focuses on the event-based scale at which material becomes entrained and eroded. Of particular relevance here are the properties (organic and minerogenic) affecting substrate stability both at the granular scale as well as the scale of the entire soil matrix from the surface to well below the depth of the root zone. Finally, it is important to recognise that, while the action of water is often the prime driver of substrate erosion, it may also facilitate other erosion processes or mechanisms (e.g. where causing undercutting and bulk-failure of marsh cliffs; Allen, 1989; Francalanci et al., 2013). Likewise, substrate erosion can also be facilitated by other processes/mechanisms (e.g. where substrates are loosened due to animal burrowing activities; Escapa et al., 2007). [Insert Figure (3) here]

Direct measurements of near-instantaneous marsh substrate resistance (both in terms of marsh edge erosion and surface erosion) are less common than indirect measurements. These direct measurements use a variety of different methods, including the shear vane, cohesive strength meter and cone penetrometer. Shear vane measurements of *in situ* undrained marsh strength, for example, ranged over three orders of magnitude from approximately 0.2 to 25 kPa in North Carolina (Howes et al., 2010). The cohesive strength meter measures the sediment erosion threshold and the cone penetrometer measures variations in shear strength and substrate composition with depth. Measurements using these techniques on a managed realignment site in Essex, UK ranged from 1.53 to 4.28 Pa and 0.6 to 260 kPa, respectively (Watts et al., 2003). While the range in these types of direct strength measurements is likely partly an artefact of the measurement method deployed (as different methods integrate over different volumes and measure different erosion processes), it also partly reflects the difference in the shear strength of marsh sediments between sites.

Independent of the method used to determine substrate resistance, it appears that, under constant forcing conditions, substrate resistance to erosion (particularly in a lateral direction) is controlled by vegetation properties, the composition of the soil matrix and biological activity therein, alongside interactions between these factors (Howes et al., 2010). This paper proposes that, for any assessment of the controls on the rate of lateral retreat, a two-part stratigraphy can be assumed (e.g. Bendoni et al., 2016). The uppermost section resistance is controlled by the combination of live biological (roots/organisms) and sediment properties. The lower (below-live-root) section resistance is likely dependent mostly on sediment properties, decomposed or decomposing organic matter and only limited deeper live root systems, the extent of which largely depend on the species present (Figs. 3a and 4). Where biofilms are present this becomes a three-part stratigraphy, with the erodibility of the uppermost centimetre to grain-by-grain erosion being influenced by the presence of biofilms. [Insert Figure (4) here]

This cliff stratigraphy may thus determine the rate and mechanism of response to driving forces, although the depth, thickness, and distinctiveness of these two stratigraphic layers likely varies considerably between locations. In some cases, for example at Scolt Head Island in North Norfolk, UK, plant roots are largely restricted to the uppermost silt/clay layer of sediment, with most roots reaching no deeper than 10-22 cm (Fig. 4; Chapman, 1960). Similarly, in Morecambe Bay, UK, the common saltmarsh grass (*Puccinellia maritima*) provides much of the marsh surface strength by creating a dense root mat, which extends ca. 14 cm below the surface, with tap roots extending deeper (Fig. 5; Allen, 1989). The lower cliff/marsh sediment column is therefore susceptible to wave attack and any tension fractures that form within this section are impeded in their vertical expansion by the presence of the root mat-strengthened upper section (Allen, 1989). The nature and rate of this response will, however, depend on substrate properties, as organic-rich sediments such as those in Louisiana, USA often have deeper roots, extending to ~30 cm depth (Howes et al., 2010). [Insert Figure (5) here]

1.3. Hydrostatic and hydrodynamic forcing

Tides, waves and storm surges exert spatially and temporally varying hydrostatic and hydrodynamic forces on an intertidal salt marsh substrate (Möller & Christie, 2018). The marsh elevation relative to the water level upon inundation governs the hydrostatic forces acting on the substrate. Using field observations at Tillingham Marsh, UK, Möller & Spencer (2002) recorded inundation depths above the marsh edge of between 0.12 and 0.84 m, with mean significant wave heights of 0.2 m, over a ten month period. These water depth and wave height conditions would have resulted in hydrostatic forces ranging from 7.4 to 9.5 kPa.

Bed shear stresses caused by hydrodynamic forces are a major control of whether sediment is entrained into suspension, eroded or deposited on the marsh surface. On a salt marsh surface, tide-induced currents are generally low (<0.2 m s^{-1}, Bouma et al., 2005; 0.08-0.33 m s^{-1}; Van der Wal et al., 2008) and bed shear stresses are typically too weak to cause sediment suspension (Wang et al., 1993; Christiansen et al., 2000). The tidal flats in front of marshes, however, typically experience much greater flow velocities of up to 1 m s^{-1} (Le Hir et al., 2000) or 0.6 m s^{-1} (Bouma et al., 2005), as do the salt marsh creeks where velocities reach up to 0.8 m s^{-1} (Bouma et al., 2005) or 0.9 m s^{-1} (French & Stoddart, 1992), potentially exerting critical shear stresses on exposed marsh margins.

Shallow water waves produce oscillatory flows in the near-bed region and typically have higher bed shear stresses than tides alone. If waves and tides occur together they interact non-linearly, resulting in bed stresses 30-40% higher than the sum of the wave and tide components (Soulsby, 1997). Induced bed shear stresses are therefore affected by wave shoaling, wave breaking, bottom roughness and local bed morphology (Nielsen, 1992). As such, relative water depth is an important parameter in understanding potential erosive forcing. Nevertheless, it is important to note that the effect of waves on a substrate requires the interaction of particular meteorological conditions with tidal levels above the threshold when the tidal flat or marsh surface floods. Consequently, the frequency and magnitude of a given hydrodynamic forcing depends on the interaction between meteorological and tidal conditions, and also the relative elevation of the marsh within the tidal frame.

On tidal flats, wave induced shear stresses mobilise the sediment into suspension (Fagherazzi et al., 2006; Fagherazzi & Wiberg, 2009; Zhou et al., 2016; Best et al., 2018) and are thought to be a key control of erosion. On the salt marsh surface, waves and tides are dissipated due to drag forces caused by the presence of vegetation (Möller et al., 1996; 1999; 2014). Energy dissipation is controlled by the vegetation properties, including not only vegetation density and stiffness (Bouma et al., 2010; Feagin et al., 2011; Ysebaert et al., 2011; Tempest et al., 2015a; Paul et al., 2016; Rupprecht et al., 2017; Silinski et al., 2018), and its seasonable variability (Paul & Amos, 2011), but also the water level above the marsh surface (Möller et al., 1999) and marsh edge morphology (cliffed vs. ramped; Möller & Spencer, 2002). However, in some cases, high bed shear stresses can be generated on salt marsh surfaces under extreme conditions. For example, Howes et al. (2010) found that bed shear stresses of 0.425-3.6 kPa were likely generated by storm waves associated with the passage of Hurricane Katrina over Mississippi delta wetlands. However, these bed shear stresses are much lower under 'normal' or 'storm' (rather than tropical storm) conditions, with Callaghan et al. (2010) being unable to record wind wave- or current-induced bed shear stresses exceeding 0.4 Pa in the Westerschelde, The Netherlands.

However, where vegetation is sparse, particularly in the pioneer marsh, vegetation patches or individual shoots are capable of increasing turbulence and thus cause local scouring (Bouma et al., 2009; Feagin et al., 2009; Silinski et al., 2016), as well as concentrating the flow between vegetation patches (Temmerman et al., 2007) which may locally enhance shear stresses (Fig. 3b).

Wave action also generates impact forces. These are particularly important at cliffed marsh edges (Mariotti & Fagherazzi, 2010). These forces are applied in a *quasi*-normal direction to the scarp and increase with tidal elevation/water depth, but fall rapidly upon marsh inundation (Tonelli et al., 2010). Using numerical simulations, Tonelli et al. (2010) found that maximum wave thrust stress can vary between 0.5-2.6 kN m^{-3}, depending on elevation and marsh edge morphology. This direct wave influence on the marsh edge has been inferred to be a major cause of observed (mapped) marsh erosion in Essex, UK (Cooper et al., 2001) and also of field-based marsh erosion measurements in the Eastern USA (Leonardi & Fagherazzi, 2014). Such sediment removal may become the main marsh loss mechanism, as shown by modelling studies (van de Koppel et al., 2005; Mariotti & Fagherazzi, 2013).

2. Properties affecting the near-instantaneous resistance of exposed marsh surfaces

A wide range of properties have been shown to affect the erosional resistance of marsh substrates exposed horizontally or vertically to the hydrodynamic forces described above. The properties affecting this resistance vary spatially and also operate on different spatial scales.

On an inter-particle (sub-millimetre) scale, resistance to applied bed shear stress is controlled by gravitational, frictional, cohesive and adhesive forces and their effects on particle interactions within the sediment (Grabowski et al., 2012). These resisting forces define the substrate erodibility, which is often quantified as an erosion threshold (Sanford, 2008). For undrained, cohesive muds, the *in situ* critical erosion shear stress is generally 0.1-1 Pa (Black, 1991). This is considerably lower than the potential hydrodynamic forces to which these intertidal sediments may be exposed, but comparable to the 'normal' bed shear stresses recorded at some sites (section 1.3). The bulk substrate resistance is ultimately constrained by physical, chemical and biological properties, including particle size distribution (PSD), water content, organic content (OC), bulk density, bulk sediment structure, porewater geochemistry, root properties and the presence of extracellular polymeric substances (EPS) (Amos et al., 1992; Black & Paterson, 1997; Grabowski et al., 2011). A summary of substrate properties and implications for substrate stability is provided in Table 1. [Insert Table (1) here]

2.1. Chemical and physical sediment characteristics

Geochemical properties, such as clay mineralogy and water geochemistry, affect electro-chemical particle attractions (Grabowski et al., 2011). For example, smectites are the most electro-chemically active mineral, followed by micas, then kaolinite (Grabowski et al., 2011). Consequently, smectites can retain water and undergo considerable expansion upon wetting (Carr & Blackley, 1986), thus becoming more erodible (Torfs, 1995; Morgan, 2005).

The sodium adsorption ratio (SAR) also influences substrate stability, as minerals absorb more water at high SAR and, when combined with a high smectite component, this can produce a highly porous and erodible substrate (Rowell, 1994; Brady & Weil, 2002). However, this behaviour is also influenced by pore water salinity. Laboratory studies have found that more saline cohesive sediment is less erodible than that with lower salinity (Parchure & Mehta, 1985). This is corroborated by field studies on tidal flats, which have found that rain during low tide can increase sediment erodibility, possibly due to the effect of rain on inter-particle attraction (Tolhurst et al., 2006a).

Another geochemical control on substrate stability is that of the presence of particular metals. Soluble iron or aluminium can increase the strength of surface biofilms (Stoodley et al., 2001; Möhle et al., 2007), and can lower the clay particle double layer thickness, thus improving cohesion and lowering erodibility (Winterwerp & van Kesteren, 2004). Similarly, field work by Crooks & Pye (2000) showed that actively accreting Essex marshes, East coast, UK had low bulk densities, high moisture contents, low undrained shear strength and were poorly consolidated, compared to those in the Severn Estuary, West coast, UK. These physical substrate properties were likely a result of porewater chemistry as low calcium carbonate content in Essex allowed sodium ions to dominate the exchange sites on clays, producing thick water films surrounding the clay particles. This resulted in slow consolidation and therefore low erosional resistance, the manifestation of which was a dissected marsh morphology (Crooks & Pye, 2000).

Within a given marsh, sediment properties vary with both distance from creeks and surface elevation. Larger particles and flocs are generally deposited nearer the creeks while finer and single particles which are not incorporated into flocs are deposited further from the creek edge (Christiansen et al., 2000; Kim et al., 2013). Grain size also fines with distance inland as marsh surface elevation increases (Horton, 1999; Strachan et al., 2016).

While distance from creeks and distance landward affect spatial variability in PSD (French & Spencer, 1993; Fletcher et al., 1994), vertical layers with distinct PSDs may also be present. Storms, for example, can deposit a layer of coarser, inorganic material (Turner et al., 2006; Schuerch et al., 2016), with deposits becoming thinner and finer in a landward direction and exhibiting a well-defined basal contact with the underlying marsh sediments (Hawkes & Horton, 2012; Schuerch et al., 2016). Storm deposits vary within a marsh, with intense storms depositing a coarser layer at higher elevations, and more frequent, smaller storms causing accretion at lower marsh elevations (Schuerch et al., 2012). Storms can also affect surface and subsurface sediment compaction, root decomposition/growth and soil shrinkage (Cahoon, 2003; Cahoon, 2006), while burial and post-depositional processes outside of storm events result in the decomposition of organic matter at depth (Spencer et al., 2003).

All of the above properties have potential implications for the material's resistance to hydrodynamic forcing. Finer grained (silt/clay dominated) or organic substrates, for example, are less prone to surface or lateral erosion than those comprising coarser, non-cohesive sediment (Houwing, 1999; Feagin et al., 2009; Ford et al., 2016; Lo et al., 2017). This is likely due to the cohesive nature of finer grained sediments. Therefore, vertical PSD variability and layering will likely mean that coarser marsh edge layers will erode preferentially, thus dictating the rate and location of cliff undercutting (Fig. 3, Fig. 5). As such, processes of marsh formation that affect variability in sediment composition and structure may affect retreat that occurs decades or centuries later.

2.2. Organic content

The organic content of a marsh substrate represents both particulate organic carbon and roots (both live and partially decomposed). While section 2.5 focusses on the latter, this section focuses on the combination of the two, as many studies use loss on ignition (which includes both organic components) to approximate organic matter content.

As with PSD, organic content (OC) of sediments also varies with elevation, with OC increasing at higher elevations (Horton, 1999; Strachan et al., 2016). While organic-rich substrates are less erodible on a grain-by-grain scale (section 2.1), Brain et al. (2011; 2015) found greater compression in sediments with higher OC and belowground root content. These sediments tended to have high initial voids ratios (low density) and therefore more open, unstable structures. Organic-rich sediments were also found to be more compressible in marshes in Massachusetts, USA (Knott et al., 1987) and in southwest England, UK (Massey et al., 2006). For example, under storm conditions in microtidal marshes in Louisiana, Florida and North Carolina, Cahoon et al. (1995) found that storm-induced hydrostatic pressure can lower the marsh elevation by tens of millimetres in the immediate storm aftermath. However, this compaction requires highly organic, compressible sediment, characteristic of marshes found on the east and Gulf of Mexico coasts of the USA.

Marsh sediment compaction is further enhanced by the decomposition of organic matter, which creates voids in the substrate, and which also reduces the substrate compressive strength against the overburden applied by newly-deposited sediments (Bartholdy et al., 2014). This then increases inundation frequency following a storm and can therefore affect plant colonisation and future organic matter content (Fig. 6). Marsh sediment compaction causes time-dependent post-depositional lowering (autocompaction; Long et al., 2006), generating increased bulk density with depth, even in the uppermost sediment horizons (Bartholdy et al., 2010a). This then affects substrate resistance as, where bulk densities are higher, the susceptibility to erosion is lower (Winterwerp et al., 2012) and substrate shear strength is higher (Watts et al., 2003). For example, young marshes generally have a lower bulk density than 'mature' marshes, so are more susceptible to erosion (van der Wal & Pye, 2004). As such, organic content affects the substrate bulk density both with depth and over time, thus contributing to vertical variations in substrate resistance. [Insert Figure (6) here]

OC and bulk density also affect within-marsh variation in compressibility. At Skallingen, Denmark, surface bulk dry density increased with percentage sand fraction but decreased with greater OC (Bartholdy et al., 2010a). This reflected the distance to sediment source (marsh edge or second order creeks; Bartholdy et al., 2010b). As such, bulk density falls with distance from the creek (Kim et al., 2013). Bradley & Morris (1990) found that compressibility was greater near the creek bank at two southeastern

US sites. At these sites, substrates were characterised by increased silt/clay content, lower sand content, lower bulk density, higher porosity and higher OC. Therefore, it seems that sediments are more compressible nearer to the sediment source (creeks or marsh edge), which could reflect the more open structures found in recently-deposited sediments, which have had little time to be compacted. Organic matter thus increases substrate resistance to near-instantaneous hydrodynamic forcing through physical (compaction) processes. Furthermore, OC and bulk density are highly inter-dependent, and also control the structure, density and compressibility of marsh and tidal flat sediments (Brain et al., 2012). Climatic changes (changes in temperature, CO_2 concentration, salinity and nutrients), grazing and human influence (through management strategies) may also affect the compressive strength of intertidal sediments through their influence on above- and below-ground vegetation and soil properties (Brain et al., 2017; Davidson et al., 2017; Spencer et al., 2017). This highlights the need to consider substrate properties in a wider context (Fig. 6).

OC also affects decomposition rates and thereby compaction and bulk density. Both vary spatially within a marsh. In the Venice Lagoon, inorganic sediment content was greater near the marsh edge, where inorganic sediment is deposited from the nearby creek, and also because, although biomass production is high, decomposition is relatively fast (Roner et al., 2016). The authors also found greater OC in the inner marsh, where there was limited sediment supply, low biomass productivity and slow decomposition, as marsh interiors aggrade more slowly (Wagner et al., 2017). As an open structure of salt marsh sediments is known to be less erodible (see section 2.1) and can compact over time (Brain et al., 2011), it is likely that, in this case, the marsh edge was less resistant to flow than the marsh interior. The presence of coarser, and thus more erodible, particle layers at the marsh edge may additionally complicate this effect, resulting in preferential erosion of particular marsh layers.

2.3. Salinity

On an inter-particle scale, higher salinity promotes flocculation as sodium ions neutralise the negative sites on clay minerals (Postma, 1967; Eisma, 1986; Mietta et al., 2009). Larger flocs generally have a higher porosity and lower density (Spencer et al., 2010), which may produce substrates which are potentially less resistant to erosion (see Grabowski et al., 2011).

Within-marsh variability in salinity largely reflects the balance between the flux of tidal water, dilution by freshwater, evaporation and sediment drainage. High salinities in the mid-marsh are due to waterlogging, which can reflect PSD at that location as the finer sediments drain more slowly and thus generally have higher water contents (Paterson et al., 2000; Kim et al., 2013). Therefore, salinity is often correlated with moisture content and clay content (Moffett et al., 2010). As PSD varies both vertically and laterally within a marsh (see section 2.1), salinity may also vary in a similar pattern (but also modified by other factors), thus affecting substrate erodibility.

As salinity affects within-marsh vegetation zonation (Silvestri et al., 2005), it can also influence the additional tensile strength provided by roots at different locations within the marsh. Salinity is also important at the between-marsh (kilometre) scale, with Alldred et al. (2017) finding that belowground root production was greater in high salinity marshes on Long Island, New York. This is corroborated by Howes et al. (2010) who found that high salinity marshes in the Mississippi delta had a higher sediment shear strength than their low salinity counterparts, which the authors attribute to deeper root systems in the high salinity marshes. Salinity is thus of importance to marsh substrate response to physical stress, both directly (through inter-particle cohesion) and indirectly (through affecting vegetation growth).

2.4. Presence of extracellular polymeric substances (EPS)

EPS are secreted by bacteria and microphytobenthos (particularly diatoms; Malarkey et al., 2015) and can form erosion-resistant biofilms (Tolhurst et al., 2008). Although evidence for the stabilising effect of biofilms comes primarily from unvegetated tidal flat environments, rather than salt marsh surfaces, it is clear that erosion-resistant biofilms can play a significant role in stabilising the substrate on or near the salt marsh platform. Their presence can increase the surface erosion threshold by up to fivefold (Le Hir et al., 2007) and they can also be found on exposed vertical surfaces. This creates spatial and temporal variation in erodibility, depending on biofilm presence or absence (Tolhurst et al., 1999; Tolhurst et al., 2006b). Given that microbiological assemblages preferentially colonise fine-grained (clay-/silt-dominated) sediments (Dyer et al., 2000), EPS presence can further amplify the higher erosion resistance of finer-grained sediments (see section 2.1).

On tidal flats, this stabilising effect of EPS was originally thought to be short-lived so, following biofilm erosion (during high shear stress; Fagherazzi & Wiberg, 2009), the underlying substrate was thought to revert to the same resistance as bare substrate (Le Hir et al., 2007). However, using an erosion chamber and sediments from tidal flats on the Jiangsu coast, China, Chen et al. (2017) demonstrated that high EPS content in the sub-surface also binds individual grains and stabilises the sediment, allowing the bed to progressively adjust to its abiotic strength following surface biofilm erosion. In these experiments, the biofilm not only increased the critical shear stress, but also the time duration that the surface could withstand threshold conditions (often by up to approximately two minutes during a seventeen minute flume experiment), with the biofilm initially degrading before sediment erosion occurred (Chen et al., 2017). The contribution of sub-surface EPS to substrate resistance was also recorded by Malarkey et al. (2015), based on laboratory experiments in a recirculating flume.

Diatoms seasonally colonise the substrate, so biofilm influence is greatest in late Spring and Summer, but can be negligible in Winter (Underwood & Paterson, 1993). Similarly, microphytobenthos biomass is greatest in the uppermost centimetre during the day, but falls overnight (Guarini et al., 2000; Blanchard et al., 2001), resulting in a diurnal cycle of productivity. Nevertheless, biofilms are thought to be the main substrate component that controls tidal flat equilibrium elevation and stability (Kakeh et al., 2016). As tidal flat lowering can affect the hydrodynamic force reaching the marsh edge, the stability of unvegetated tidal flat surfaces is a key control on salt marsh stability and (see section 3 below). Similarly, the relative importance of EPS for substrate stability is probably greater on the tidal flat than the salt marsh (as vegetation is absent and thus incident forcing is likely higher). However, a lack of work into EPS on salt marsh platforms means that, to the best of the authors' knowledge, the role of EPS for marsh substrate stability is poorly quantified. For a full review on biostabilisation, see Paterson et al. (2018).

2.5. Presence of live vegetation and roots

Erosion on the marsh platform itself is often minimal (Temmerman et al., 2005; D'Alpaos et al., 2007; Spencer et al., 2015b) and this is partly attributed to the presence of vegetation, which can stabilise sediment, prevent surface erosion and reduce boundary layer water velocities and thus hydrodynamic energy (see section 1.3).

As well as influencing the hydrodynamic forcing applied to the substrate layer itself, the motion (bending) of above-ground vegetation under waves/currents can also destabilise surface sediment directly (Spencer & Möller, 2012), by producing pockmarks following the removal of individual vegetation elements. Vegetation stems may break when hydrodynamic forcing reaches a species-dependent critical mean orbital velocity (0.3-1.2 m s^{-1}; Vuik et al., 2018), which can then reduce the wave attenuation capacity of salt marshes, thus increasing the erosional forces. The fact that plants are present both above and below ground challenges the conceptual distinction between soil-external and soil-internal processes. For example, field and flume studies show that coarser, belowground organic material (roots) may move under wave action and dislodge sediment, thus potentially enhancing wave-induced erosion both at the surface and on the vertical marsh face (Coops et al., 1996; Feagin et al., 2009).

Notwithstanding the close connection between the above- and below-ground attributes of salt marsh surfaces, the contribution of below-ground biomass to marsh substrate stability has been under-researched compared to the above-ground component (Bouma et al., 2014). For a variety of different environments, Gyssels et al. (2005) clearly demonstrated how roots increase substrate stability and thus erosion resistance. Evidence for this has been found particularly in the upper section of salt marsh cliffs (Mariotti & Fagherazzi, 2010) and roots have been recognised as important for reducing erodibility and thus marsh lateral erosion rates (Silliman et al., 2016; Lin et al., 2016; Lo et al., 2017; Sasser et al., 2018). Roots can increase marsh stability and reduce sediment erodibility (Wang et al., 2017), both on the marsh surface (Coops et al., 1996; Chen et al., 2012; Francalanci et al., 2013), and at the marsh edge (Deegan et al., 2012; Silliman et al., 2012). This is particularly important in Winter, when the lower aboveground biomass reduces the wave attenuation capacity. As a consequence, incident hydrodynamic energy may be higher (Schoutens et al., 2019). However, the role of belowground roots for marsh stability will partly depend on the species, and root structures, present (Fig. 4), as well as factors such as soil aeration, as increased soil aeration can increase plant biomass (Linthurst, 1979).

Numerous studies in freshwater environments have established that the effect of roots on substrate strength is generally twofold: roots increase aggregate stability (Pohl et al., 2009; Du et al., 2010; Li & Li, 2011) and reinforce the soil matrix by providing tensile strength (Gray & Barker, 2004; Vannoppen et al., 2015). Soil aggregate stability is a key component of soil structure (see Amezketa, 1999). Soil aggregates are defined as a cluster of particles between which the forces holding the particles together are greater than those between adjacent aggregates (Martin et al., 1955). Live roots increase aggregate stability by providing a surface for aggregate formation (Reubens et al., 2007), by producing root exudates which bind the soil (Jones et al., 2009) and by increasing substrate particulate OC which in turn increases soil structural integrity (Bronick & Lal, 2005; Fattet et al., 2011). As increased aggregate stability reduces sediment erodibility (Knapen et al., 2007; Wang et al., 2012), roots reduce the sediment erosion caused by waves and currents acting over the marsh surface and along the cliff edge (i.e. particle detachment due to exceedance of the critical shear stress). Plant roots therefore directly reduce substrate erodibility through increasing soil aggregate stability, an effect which is enhanced by increased root density or longer roots in a given substrate volume (root length density; De Baets & Poesen, 2010; Knapen & Poesen, 2010; Zhang et al., 2013).

While the soil matrix generally becomes stronger with compression, roots provide tensile strength, therefore the effects of both components are complementary to each other (Simon & Collison, 2002). Tensile strength provided by roots varies seasonally, being highest in the summer months (Morris & Haskin, 1990). The mechanical reinforcement provided by roots will depend, amongst other factors, on root depth, density and diameter (van Eerdt, 1985; Mickovski et al., 2007; 2009; Stokes et al., 2009; Loades et al., 2010; Vannoppen et al., 2016). These controls vary with vegetation species and salinity (Visser et al., 2000; De Baets et al., 2008; Mitsch & Gosselink, 2015).

Using cores from the Northern Adriatic Sea and volume loss in a wave mesocosm as a measure of erodibility, Lo et al. (2017) demonstrated that belowground root matter can increase the erosional resistance of sandy marsh sediments more than in silt/clay-dominated substrates. This enhanced resistance to concentrated flow erosion is particularly evident with a fibrous root structure, rather than if tap roots dominate the sediment column (Vannoppen et al., 2015; 2017). Nevertheless, for landslide or failure-type processes, Ghestem et al., (2014) found that vertical tap roots were more effective at stabilising a slope in the laboratory than a root structure with a mixture of oblique and vertical roots, or one consisting of rhizomes with offshoots. However, quantitative studies relating measured substrate shear strength, root properties, and detachment rates in any environment are scarce, due to the difficulties in measuring substrate shear strength in rooted soils (Katuwal et al., 2013; Yu et al., 2014).

Increased substrate density and intact roots increase the substrate shear strength (van Eerdt, 1985; Mickovski et al., 2009), particularly in the upper part of the sediment column. Therefore, the lower stratigraphic column and/or localised areas of waterlogging, where roots are largely decomposed or dead, are likely to have reduced strength, such as in pools (Schepers et al., 2017) and below 30 cm depth (Howes et al., 2010; Turner, 2011). However, at least for deeper soils, this may be partially counteracted by greater bulk/particulate organic matter contents and compaction (Allen, 1999) and thus a stronger soil matrix. Using erosion pin measurements in the Venice Lagoon, Bendoni et al. (2016) corroborated this upper cliff root reinforcement, above a weaker lower cliff, and found that a less resistant cliff toe can lead to bulk failures and increase the cumulative retreat rate, thus partially negating the stabilising influence of near-surface roots. This root reinforcement in the upper layers of the marsh stratigraphy was highlighted by Allen (1989), who found this to be particularly important in marshes in Morecambe Bay and the Solway Firth, Northwest England. At these sites, the sediments were sand-dominated and susceptible to grain-by-grain erosion in the lower layers, but were strengthened considerably in the upper layers by roots. This was less apparent in muddier sediments in the Severn estuary. As a result, the Morecambe Bay and Solway Firth marshes appeared to retreat through cantilever- or beam failure following undercutting (Allen, 1989).

Decomposition is a key control on the strength of the sub-root-mat layer and varies with geochemical substrate properties, often being positively correlated with the presence of interstitial phosphorous and inorganic nitrogen (Mendelssohn et al., 1999). The rate of decomposition also depends on both the nature of the organic material (Duarte et al., 2010; Jones et al., 2016) and the nutrient content of the sediment (Turner, 2011). For example, the herbaceous stems of the generally woody scrub *Arthrocnemum macrostachyum* have little lignification and so decompose faster than other components (Simões et al., 2011). Also, salt marshes with increased nutrient levels see increased microbial decomposition of organic matter, and reduced biomass allocation to belowground plant components, both of which reduce the structural integrity of creek banks (Deegan et al., 2012). As such, the extent to which decomposition has taken place will likely affect the tensile strength provided by any remaining, partially-decomposed roots in this lower section.

The linkages between vegetation/root type/density, organic matter, and compaction, amongst others, are illustrated in Fig. 6. There is evidence that lower substrate erodibility occurs in locations with increased plant species richness and greater root biomass (Ford et al., 2016). This is particularly important in erosion-prone sandy sediments, such as in Morecambe Bay, UK compared to the relatively erosion-resistant clays of Essex, UK (Ford et al., 2016).

Although vegetation generally increases substrate resistance, Feagin et al. (2009) used flume and field studies to provide evidence that vegetation may not directly reduce lateral marsh edge erosion but, rather, may indirectly influence the erosion rate by altering soil properties (e.g. density, PSD). Chen et al. (2012) also noted that vegetation influences substrate properties and erodibility, as the relative importance of roots and downcore consolidation for creek bank stability depends on vegetation type. This vegetation-sediment interaction means that sediments colonised by certain species (e.g. the woody shrub sea purslane *Atriplex portulacoides*) are more resistant to flow-induced erosion, while those colonised by other species (e.g. the sea rush *Juncus maritimus*) provide greater resistance to mass movement. Using micro-CT scanning to characterise the root structure at the same site in Southern England, Chen et al. (2019) inferred that the fine, but dense root mat provided by *Atriplex portulacoides* plays a key role in providing resistance to flow-induced erosion. As such, the vegetation type (and thus root structure) is important, and seems to have a greater stabilising effect on cohesive sediments, but this stabilising effect also depends on the substrate composition (and thus consolidation). Again, this demonstrates the complex links between various substrate components (see Fig. 6).

2.6. Presence of voids and cracks

Voids or cracks within the substrate may be particularly evident at the marsh edge and can aid the initiation of marsh edge failures. As noted in section 1.2, marshes can erode laterally by cliff undercutting, followed by toppling or slumping failure of the upper cliff. Toppling failures are often instigated by tension cracks, quasi-vertical cracks produced from the surface down as the outer part of the cliff or bank begins to topple (Francalanci et al., 2013). This happens particularly when there is water inside the tension crack or where there are low water levels in front of the marsh edge (Bendoni et al., 2014). Tension cracks form in late summer due to substrate shrinkage and reduced moisture content (Allen, 1989; Morris et al., 1992). This reduced moisture content can occur due to lower rainfall in the summer months or also as a result of low summer spring tides which allow time for sediment desiccation and cracking, as is the case on the UK East coast (Smith et al., 1998; Spencer et al., 2012). However, tension cracks may themselves also form due to tidal fluctuations and the resultant cyclic oscillations of mean and effective stresses exerted by the tides (Cola et al., 2008). As substrate shrinkage and moisture content are known to vary with sediment type, tension crack formation (and thus the occurrence of toppling failure) likely also depends on intrinsic substrate properties (Fig. 6).

Deeper subsurface stratigraphy can influence lateral water pathways in both natural (Xin et al., 2012) and restored marshes (Tempest et al., 2015b). Where marshes have developed in coastal embayments, they are often characterised by a high-permeability sandy layer overlain by a lower permeability silt/clay layer (Xin et al., 2009; Carol et al. 2011). Based on modelling analyses, Xin et al. (2012) found that the underlying sandy layer facilitated drainage of the upper layer during the falling tide. While a reduction in water content would likely directly increase the substrate shear strength (Watts et al., 2003), the decline in local soil water saturation may increase aeration of the uppermost soil layer, which can indirectly improve plant growth (Li et al., 2005; Xin et al., 2010). This would increase substrate strength. Preferential flow paths through the uppermost soil layer to the lower soil layer can also be initiated due to bioturbation by invertebrates and the subsequent creation of macropores (see below; Xin et al., 2009). On a smaller scale, the deposition of coarser storm-related units will also affect water movement and thus water content, as coarser substrates can drain faster. This effect on water movement will affect the erosion of particles situated along the pathways of water flow.

2.7. Presence of macrobenthos/invertebrates

Macrobenthos can increase substrate porosity by creating macropores (voids) within the sediment through burrowing and bioturbation. At the Skeffling mudflat, Humber Estuary, UK, Paterson et al. (2000) found that porosity increased towards the shoreline, likely due to a smaller particle size and thus increased water content (as drainage was poorer) and a higher macrobenthos density. As increasing porosity lowers the bulk substrate yield strength (the applied stress at which the resultant material deformation is irreversible; Barry et al., 2013), and subsurface porosity is a good predictor of surface erodibility (Wiberg et al., 2013), invertebrates directly affect marsh substrate strength.

Surface deposit feeding bivalves such as *Macoma balthica, Scrobicularia plana* and *Cerastoderma edule* bioturbate surface tidal flat sediments, which reduces the density of the sediments and increases sediment erodibility (Widdows et al., 2004). This has been found for a variety of sites, including the Molenplaat tidal flat, Westerschelde, The Netherlands (Widdows et al., 2000a), mudflats in the Humber Estuary, UK, (Widdows et al., 2000b) and also in laboratory flume studies (Widdows et al., 1998). Other macrobenthos (e.g. *Hydrobia ulvae* and *Corophium volutator*) have been found to have a similar 'bio-destabilising' effect on intertidal substrates on both tidal flats and salt marshes in Essex, UK (Widdows et al., 2006). There may be some temporal variability associated with this grazing activity; *Macoma balthica,* for example, is known to increase in population density following cold winters (Widdows et al., 2000b). As such, inter-annual changes to the near-instantaneous resistance of intertidal substrates, has been correlated to inter-annual changes in these "bio-destabilising" biota (Widdows & Brinsley, 2002).

In the Bahía Blanca estuary, Argentina, Escapa et al. (2007) found that substrates inhabited by crabs generally had a higher water content and lower shear strength, thus implying that bioturbation and biological processes affect, or are affected by, the substrate properties. However, in the same estuary, Escapa et al. (2008) noted that crab burrows can affect sediment trapping and removal, with crab burrowing promoting sediment trapping in the inner marsh and on the open mudflat, but also increasing marsh edge sediment erosion. As such, crabs may produce contrasting geomorphic impacts even within a given marsh system.

Crab burrowing induced oxidised conditions in the upper 10-15 cm of a *Spartina alterniflora* dominated marsh in South Carolina, USA, thus allowing decomposition of belowground biomass, which lowered the substrate shear strength (Wilson et al., 2012). Therefore, bioturbation can increase porosity and reduce belowground live biomass and bulk density, which reduce substrate strength. However, as invertebrates generally colonise fine-grained sediments (Dyer et al., 2000), the influence of invertebrates will likely vary laterally and vertically within the marsh-tidal flat system, producing spatial variability in erodibility. Separating cause and effect is also difficult, as invertebrates both influence the substrate properties, but their choice of location and their abundance is also determined by the initial substrate properties. Once again, this demonstrates the complex inter-connections between individual resistance-related substrate properties (see Fig. 6).

Biological activity (e.g. crabs, ragworms and amphipods) can increase sediment susceptibility to erosion by waves/tides and can re-organise sediment structure and microtopography (de Deckere et al., 2001; Escapa et al., 2007; Szura et al., 2017; Vu et al., 2017). Ragworms and amphipods have also been proposed as a cause of marsh erosion (Hughes & Paramor, 2004; Paramor & Hughes, 2004), however this argument has been questioned due to a lack of procedural control (Wolters et al., 2005).

2.8. Presence of animals (grazing)

Marsh grazing can take many different forms (e.g. grazing by sheep, cattle, geese and others), but all types of grazing likely affect marsh substrate stability. While grazing in some locations increases vegetation species richness (Ford et al., 2013a), grazing can also reduce vegetation species diversity, with grasses such as *Puccinellia spp.* frequently dominating grazed sites (Kiehl et al., 1996). What is clear, however, is that grazed sites generally have a lower marsh canopy height and reduced above-ground biomass and litter volumes (Ford et al., 2013b; Davidson et al., 2017). It can be argued that a lower marsh canopy height will reduce the wave attenuation capacity of a marsh, thus affecting the driving force *versus* resisting force balance. Similarly, grazing can also create patches of bare ground (Bakker, 1985), with the expectation that such patches will be considerably more erodible than those with a vegetation cover. Such bare soil patches also generally undergo higher rates of evaporation, resulting in higher soil salinity, which can further reduce vegetation species richness in the surrounding area (Di Bella et al., 2014; 2015).

Sediment compaction by grazing due to the repeated trampling by animals is also a well-known phenomenon (e.g. Lambert, 2000), and is most prevalent in clay/silt/organic-rich sediments, where compaction can produce anoxic conditions and can thus reduce decomposition rates of organic matter (Schrama et al., 2013). At least with large grazers (e.g. cattle), this can result in increased biomass distribution towards the roots and thus increased belowground biomass (Elschot et al., 2015), which can increase stability (see section 2.5). While compaction at depth is expected due to autocompaction (compaction of sediment under its own weight; Allen, 1999), grazing-induced compaction is generally only apparent in the uppermost sediment layers (upper 20 cm; Elschot et al., 2013), where it can increase the sediment bulk density. Such compaction may thus reduce erodibility of the marsh surface (Pagès et al., 2019). The effect of grazing can therefore affect soil stability via a range of interconnected processes through influencing the presence, density, and type of biota present, as well as soil chemistry and redox potential (Davidson et al., 2017).

3. Marsh substrate stability and landform change

This paper has focused on how a number of attributes condition substrate response to hydrodynamic forcing over near-instantaneous scales (i.e. an immediate driving force applied by water and the resistance of the substrate to this due to its chemical, physical, and biological properties). It is clear however that, while often studied in isolation to determine the relationship between individual attributes and substrate stability, many of these attributes are in fact closely interlinked. Furthermore, substrate stability may alter over time, as processes such as soil formation and organic decomposition take place over years to decades and result in a cumulative effect on resistance to forcing. As the scale of interest moves to larger spatial scales and longer timescales, morphodynamic feedbacks (Fig. 2) as well as the complex interactions between substrate properties, become important (Fig. 7). It therefore becomes necessary to explore the importance of (a) the possible implications of relationships between individual attributes and their joint effect on substrate stability, (b) the role of the wider geological, environmental, and human management context that may determine these interrelationships and (c) the morphodynamic feedback that connects substrate formation to landform evolution and *vice versa*. [Insert Figure (7) here]

3.1 Potential connectivity between substrate attributes

Several studies have linked sediment type to erodibility, but often refer to the substrate as either "sandy" or "muddy", based on at worst, qualitative impressions and, at best, the median grain size (e.g. Bouma et al., 2016) and/or use solely the PSD as an indicator of sediment properties (e.g. Bendoni et al., 2016). While these studies can provide vital information on the role of PSD in determining soil stability, physical and chemical sediment properties, such as PSD, clay mineralogy, and organic carbon, are likely to be tightly linked (Grabowski et al., 2011). Therefore future studies should more explicitly acknowledge and address the spatial and temporal variability of such interrelationships between substrate properties. This would improve understanding of how substrate properties, and thus the stability of exposed marsh sections, might vary in the future.

In addition to the interrelationships between properties, it is important to better understand how those properties change over time and what drives such change, thus allowing forecasting of how substrate properties might change in future. For example, the fact that root growth, which influences stability, is itself affected by soil chemistry. Soil chemistry also acts as a control on stability in its own right but, over longer periods of time, can determine root growth and structure (Bouma et al., 2001a). Notwithstanding variability in root type between plant species (e.g. Bouma et al., 2001b), root growth and soil chemistry may thus, amongst other influences, result in the particular root network structure, density and depth that become important for the stability of the marsh substrate at any given point in time. Little is, as yet, known of such time-dependent interactions.

In summary, while existing studies suggest patterns of spatial variability in some properties (e.g. PSD, OC; Kim et al., 2013; Strachan et al., 2016), this review shows that future studies need to focus more on how these properties link together to translate into the bulk resistance of the substrate to hydrodynamic forcing (Fig. 6). A better understanding of within-marsh spatial variability in substrate properties and their interactions may allow us to derivation of spatially-distributed substrate stability proxies. These proxies could then be used in two- or three-dimensional morphodynamic models to forecast future marsh change and can then be trialled against direct observations of marsh change.

Fig. 8 illustrates schematically how two or more parameters could be combined into such an index. Fig. 8a depicts a hypothetical marsh platform with multiple bifurcating channel (creek) networks, interior bare ground and marsh margin shell sand (chenier) ridges. Fig. 8b shows how particle size varies within a marsh, with larger particles near the creek edges and marsh edge (see section 2.1). Fig. 8c shows how organic content increases with elevation (see section 2.2). Similar layers for other substrate properties could be produced, and converted into weightings across the layer to summarise how important this particular property is for providing marsh resistance in a given location. Various layers of substrate properties (i.e. layer B and layer C) could then be combined linearly or non-linearly to produce an overall map or index of marsh resistance (Fig. 8d), however constraining these functions from which to create the index remains a challenge. A similar analysis could be created for specific sediment depths within a marsh. [Insert Figure (8) here]

3.2 Context-dependency and spatial variability of substrate resistance

It is clear from the literature reviewed above that salt marsh substrate properties are highly dependent on regional (e.g. geological and climatological) context. It is also clear that this regional context, alongside smaller scale and within-marsh variations in physical, chemical, and biological process regimes causes substrate resistance to be highly spatially variable between and within marsh systems. Fig. 6 lists some of the contextual controls on substrate stability, how these may interact and also how contextual factors influence the marsh attributes, and the attributes and processes influence each other in an iterative manner over time.

At the regional scale, geology, climatology, sea-level trends, and other factors form key controls on salt marsh processes, evolution and, thus, substrate properties (Fig. 7). Geological context, for example, will exert a control on clay mineralogy as a determinant of inter-particle cohesion and thus susceptibility to erosion by water. Through its effect on plant growth, hydrology, and soil biogeochemistry, the climate (and therefore the future climate) exerts an important control on root density, soil salinity, organic matter contents etc.. All of these properties have been shown to relate to substrate resistance to hydrodynamic forcing (Fig. 6; Howes et al., 2010; Wang et al., 2017; Sasser et al., 2018).

At the individual marsh scale, hydrodynamic exposure and human management (e.g. Deegan et al., 2012) are examples of processes that can exert marsh-wide controls on substrate resistance/stability (Fig. 6), albeit with potentially significant within-marsh variability. A more energetic hydrodynamic setting, contrasting offshore geology or different fluvial discharge, for example, may result in marshes composed of coarser sediments (such as in the case of Morecambe Bay, UK; Pringle, 1995). The active management (e.g. grazing) or restoration (e.g. through managed realignment) of salt marshes is widely recognised as affecting vegetation and sediment properties (Kadiri et al., 2011; Spencer et al., 2017). It is thus likely to constitute an important control on the attributes relating to substrate resistance to hydrodynamic forcing, not least due to the tight connection between biological, physical, and chemical processes all of which have been shown to control substrate resistance (Chapman, 1941; Adam, 1978) (see also section 3.1 above).

At the within-marsh scale, one of the more obvious spatial patterns in salt marsh substrate properties controlling their response (in terms of lateral retreat) to hydrodynamic forcing is the stratification of the marsh. This divides the marsh into a more or less distinct upper, root dominated, and lower, more compacted and often more homogenous layer, yet many studies that report on substrate resistance do not explicitly acknowledge this vertical layering. In the horizontal dimension, the armouring and cohesive effect of biological organisms, such as diatoms and algae, can be very localised with individual patches of higher resistance less than meters in size (Weerman et al., 2012). Furthermore, the existence of more complex, three-dimensional (sub-)surface structures such as chenier or storm deposits of coarser gravel or shell materials reported on some US and UK marshes (Greensmith & Tucker, 1975; Visser et al., 2000; Hawkes & Horton, 2012) introduces significant within-marsh variability in erosion resistance.

To fully understand why and how an individual marsh may respond to a particular hydrodynamic forcing event, it thus becomes necessary to understand two things. Firstly, the regional and local context within which the marsh is situated and secondly, the horizontal and vertical spatial variation in marsh substrate properties within the marsh system. This could potentially be achieved through extensive field surveys and an ability to identify specific substrate properties from aerial or drone imagery. Such an understanding would make it possible to assess the role such variations in substrate properties play in the longer term evolution of the salt marsh landform.

3.3 Role of substrate properties in salt marsh morphodynamics

Salt marsh morphodynamics refer to the inter-annual to decadal change in marsh morphology. When considering the role of individual substrate properties in such longer-term (decadal scale) landform evolution, it is important, to note that the salt marsh landform is tightly associated with adjacent sedimentary units, most importantly, the fronting tidal flat or creek bank/slope and any barriers located to the seaward side. Unvegetated surfaces provide less resistance to hydrodynamic forcing than vegetated marshes (Kirwan et al., 2010; Spencer et al., 2015b) and wave energy is dissipated less than on the marsh (Möller et al., 1996; 1999). The resulting higher hydrodynamic energy over the unvegetated adjacent surfaces may thus result in a higher relative mobility of tidal flat compared to marsh sediments, tidal flat lowering, and the formation of marsh cliffs (Bassoullet et al., 2000; O'Brien et al., 2000), particularly during winter (Callaghan et al., 2010). It can also release sediments that then contribute to accretion on the marsh surface (Reed et al., 1985; Fagherazzi & Priestas, 2010; Fagherazzi et al., 2013; Schuerch et al., 2019). Given identical forcing conditions, the evolution of the marsh over longer (annual to decadal) time scales is thus not merely a function of substrate properties of the marsh and those exposed at the cliff, but also of those of the fronting tidal flat (Mariotti & Fagherazzi, 2010).

Evans et al. (2019) provide evidence for the importance of morphodynamic feedbacks in driving salt marsh morphological change through time. Edge erosion can, for example, inhibit further marsh loss when eroded material is deposited on the tidal flat, lowering the water depth and reducing wave power at the vegetated margin (Bendoni et al., 2016; Mariotti & Canestrelli, 2017).

Marsh edge change can also be cyclical, with marshes undergoing phases of progradation, followed by erosion. Such behaviour has been noted on marshes in Morecambe Bay, UK (Pringle, 1995) and in The Wash, UK (Kestner, 1962) and has been linked to the migration of tidal channels. Cyclical expansion has been noted at Raahede, Denmark (Pedersen & Bartholdy, 2007). Here, formation of a shore-parallel creek landward of the marsh edge, followed by deposition of fine-grained sediments on patches of relatively high elevation on the seaward side of the creek was shown to establish a new marsh, resulting in a stepped morphology containing relict marsh cliffs.

Where the above mechanisms have led to the exposure of marsh substrates at a near-vertical cliff face, however, substrate properties likely exert a strong influence on how marsh margin morphology evolves. While the marsh elevation relative to the tidal frame controls where waves act (Tonelli et al., 2010), evidence also exists for cliff undercutting at points of substrate weakness by tidal and wave action (see Fig. 3), followed by cantilever, toppling failures or gravitational slumping once the overlying section weight exceeds the combined sediment and tensile root mass strength, causing episodic failure under gravity (Allen, 1989; Allen, 2000; Francalanci et al., 2013;Bendoni et al., 2014; Turner et al., 2016; Leonardi et al., 2018). This mass wasting can significantly increase suspended sediment concentrations (Ganju et al., 2013) and may result from local depth-dependent wave field variations at the cliff toe (Bendoni et al., 2016). Mass wasting can account for 50-70% of total marsh edge retreat in some locations, with the removal of particles from the marsh margin through particle entrainment and/or hydraulic pressure (impact forces) likely accounting for the remaining erosion (Priestas et al., 2015). The movement of plant roots can assist the dislodgement of material (Feagin et al., 2009). Our understanding of the precise role of each process (mass wasting, particle entrainment, root movement) and the interaction of all these processes in cliff retreat is largely limited by a lack of direct observations as most studies rely on before-after tidal/wave impact cliff surveys.

Models of marsh evolution under future climate change scenarios frequently use an erodibility coefficient to describe the erosion resistance of the substrate (e.g. Mariotti & Carr, 2014). In van de Koppel et al. (2005)’s model, for example, the cliffed boundary retreats at a rate modulated by the incident wave forcing, tidal flat dynamics and marsh cliff stability. Cliff stability is assumed to be a spatially homogenous property and is poorly defined through a fixed critical erosion shear stress. As such, there are neither direct observations of marsh edge erosion processes, nor are there models which adequately parameterise the properties identified above as influencing rates and location of erosion.

Marsh edge retreat may also represent a form of ‘self-organisation’ whereby marsh expansion into deeper water reaches an exposure threshold triggering cliff formation and recession (Kestner, 1962; van de Koppel et al., 2005; Singh Chauhan, 2009). Wang et al. (2017) found that the relative importance of external *versus* intrinsic factors for marsh edge erosion in the Westerschelde, The Netherlands, depends on the scale of analysis. Pioneer vegetation fronting the cliff and wind exposure were most important at larger landscape scales, foreshore morphology at intermediate within-site scales, and differences in cliff erodibility (due to sediment composition and below-ground biomass) at local centimetre-metre scales.

This review has highlighted several key areas for future research. Firstly, the need to understand both the horizontal and vertical variation in marsh substrate properties. Secondly, the necessity to determine precisely how these substrate properties act together to affect the bulk resistance of the substrate to hydrodynamic forcing. Thirdly, the need to better understand the spatial and temporal variability of interrelationships between substrate properties and therefore how these properties and thus stability might vary in the future.

An improved understanding of the spatial variability of tidal wetland properties, and their influence on the rates and occurrence of erosion processes will help ascertain how these properties may alter morphodynamic behaviour over long timescales (decades-centuries). In practice, this increased understanding will both improve projections of future marsh extent, and will also have key implications for the success of future salt marsh restoration and re-creation (e.g. in ‘managed realignment’) schemes. Such schemes are becoming increasingly popular for sustainable flood risk management and habitat creation, particularly in Europe (Esteves & Williams, 2017). The focus, however, has largely been on restoring or reproducing the ‘natural’ marsh vegetation types and vegetation structure, to improve habitat provision and/or biodiversity (Morris, 2012). Considerably less attention has been paid to the stability of the marsh soils that are produced as a result of such restoration practices. For this, an improved understanding of both the spatial variability and interdependence of sedimentological, chemical, hydrological and geotechnical properties is required, as well as how these properties may alter morphodynamic behaviour and thus stability over longer time-scales.

4. Summary

The body of literature linking individual physical, chemical, or biological properties to the susceptibility of salt marsh substrates to erosion by near-instantaneous hydrodynamic forcing has grown steadily over the past two decades. Less is, however, known about the way in which and the degree to which individual substrate properties interlink to affect substrate stability over time and across space (as we illustrate schematically in Fig. 6).

Over time, the dominant factors affecting substrate resistance will vary. In a ‘young’ marsh, PSD and thus offshore or terrestrial geology may be most important. As a marsh ages, the cumulative impact of marsh processes and interactions over time become more dominant (French & Stoddart, 1992). Factors such as management history (grazing or turf cutting) may become significant through their influence on plant diversity and thus root properties (e.g. Davidson et al., 2017). This time-dependence is further amplified as morphodynamic feedbacks are instigated (e.g. Evans et al., 2019) and forcing and resistance/stability themselves become interlinked.

Future studies must consider co-variance between properties as well as their combined influence on substrate stability (Fig. 6) and illuminate better some key relationships between attributes and processes, such as how roots affect the substrate OC or porosity, especially at depth, or how roots themselves directly contribute to substrate strength.

Finally, a better understanding of within-marsh spatial variability in substrate properties and their interactions, may allow researchers to derive spatially-distributed substrate stability proxies. Ultimately, and alongside a wider consideration of sediment delivery, sea level rise, human management actions, etc., such an approach is necessary to improve the success of managed realignment schemes, and to improve our ability to understand and predict how particular marshes will respond to changes in biological, climatological, and hydrodynamic conditions resulting from future climate scenarios.

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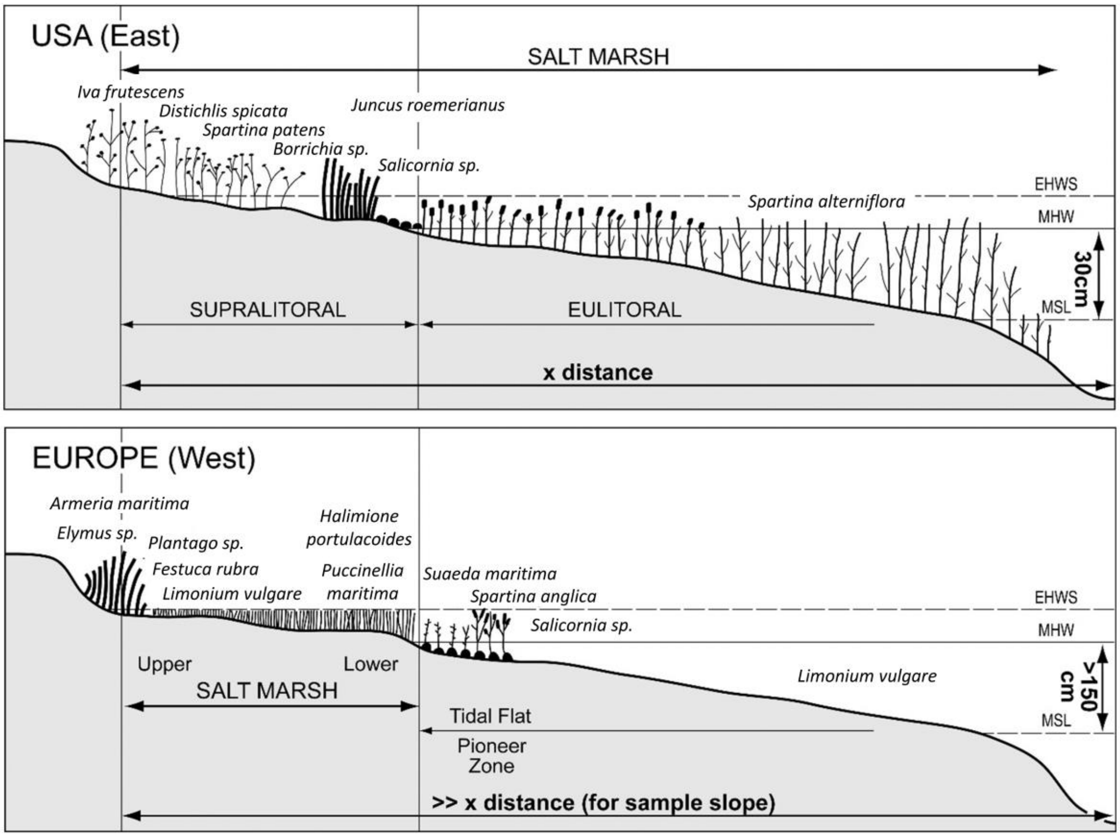

Figure 1: Comparison between Northwest European marshes and those on the Eastern coast of the USA. Modified from Dame & Lefeuvre (1994).

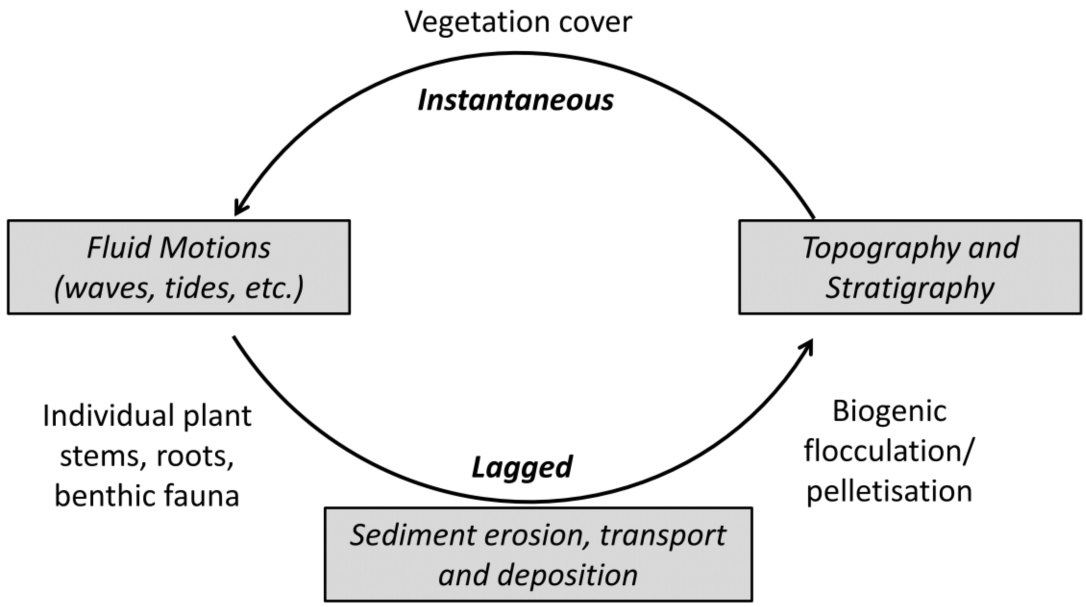

Figure 2: Morphodynamic feedbacks in salt marshes. Modified from: Möller (2012)

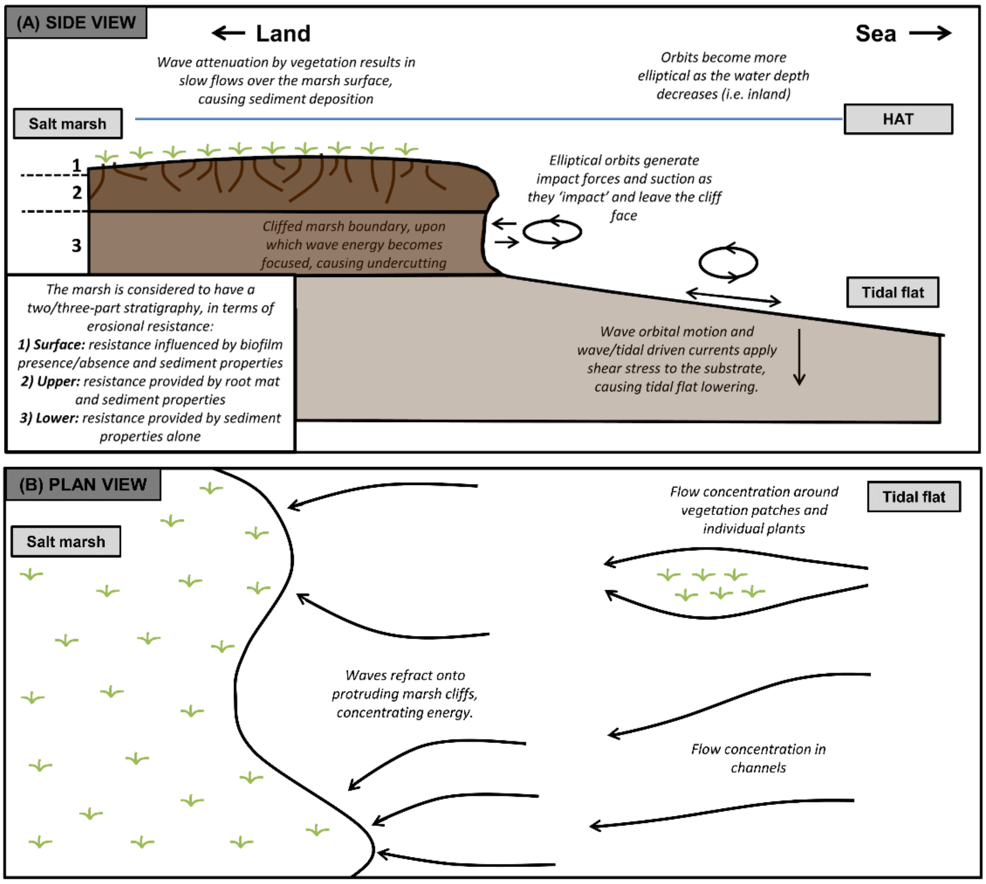

Figure 3: Hydrodynamic forcing on the tidal flat surface, marsh cliff and marsh surface in side view, using the example tidal level of Highest Astronomical Tide (HAT) (a) and plan view (b).

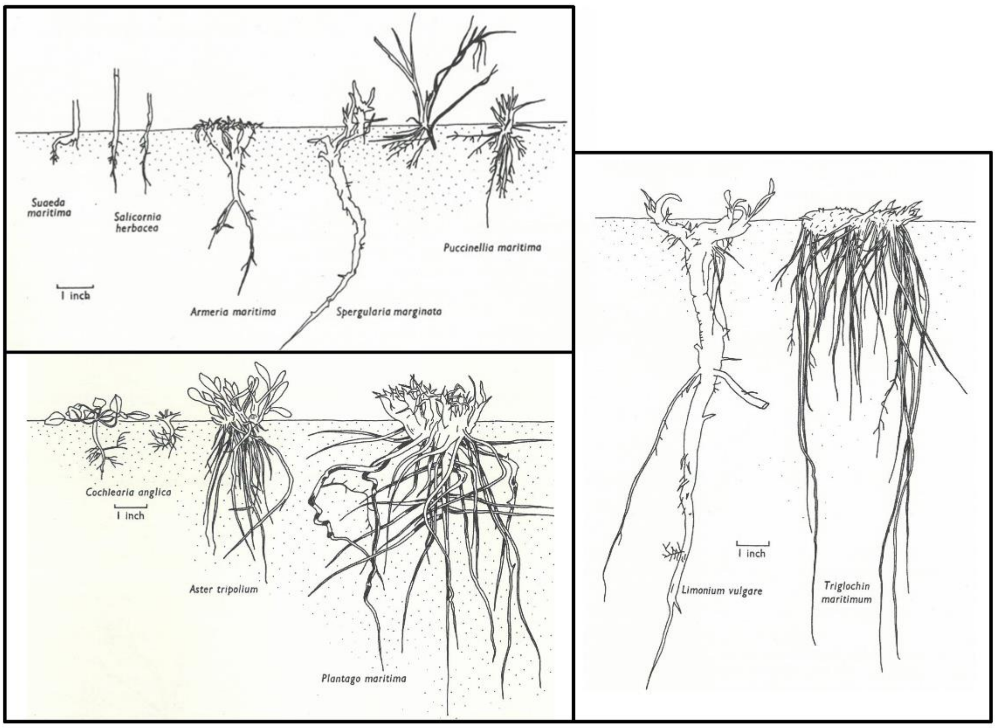

Figure 4: The varying lengths and structures of root systems for species from Plover Marsh, North Norfolk, UK, for species growing at 2.96 m ODN (as of 1934). One inch is approximately equal to 2.54 cm, therefore the Limonium vulgare root extends to approximately 25 cm depth. Taken from: Chapman (1960), pg. 87-89.

Figure 5: Example of undercutting at the base of the cliff, while the upper cliff overhangs, and appears to be held in place due to tensile strength provided by the roots. Photo by I. Moeller taken at Warton marsh, Morecambe Bay in July 2018. The knife in the photo is approximately 20 cm in length.

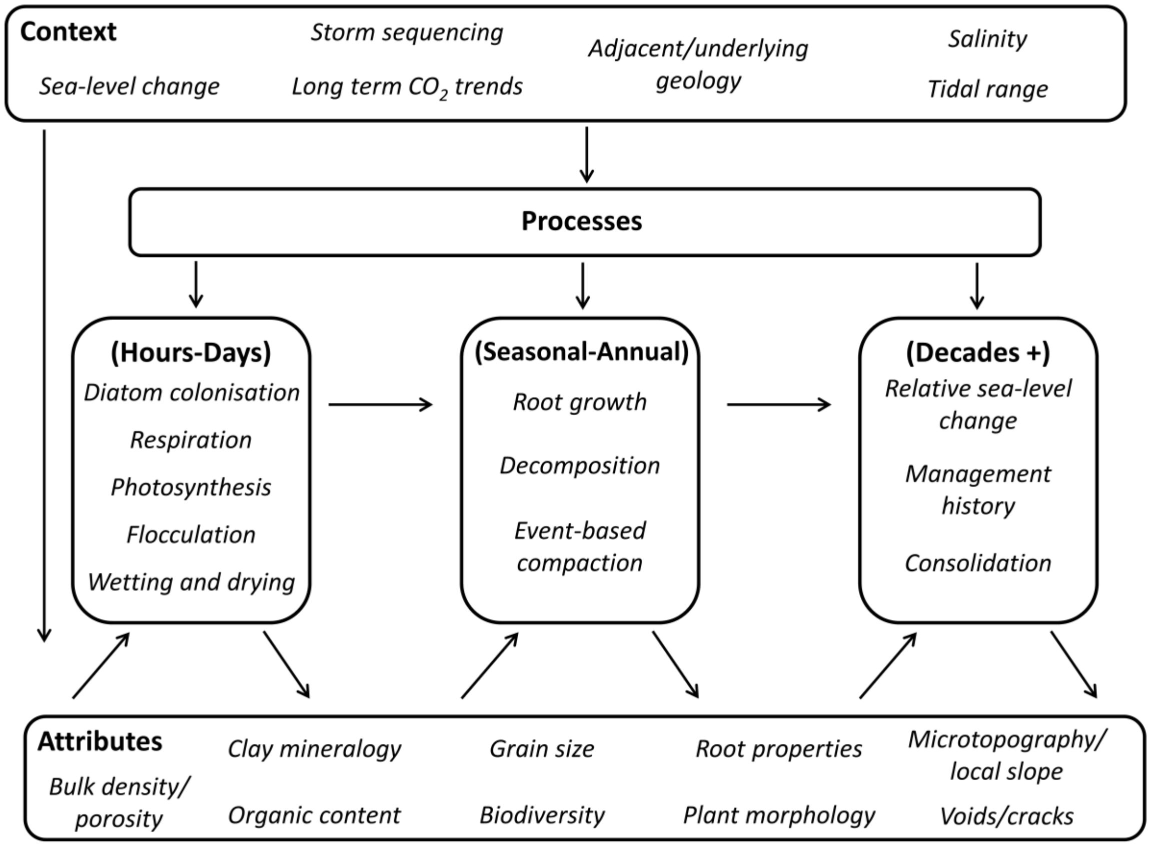

Figure 6: The cumulative impact of a suite of processes, attributes (marsh/tidal flat properties), and contextual factors (external influences on the system) that affect the stability of a sub-metre block of marsh substrate at a given point in space and time. The timescale bar relates to the timescale over which the processes operate (hours-days in the far left box, through to decades and longer in the far right box), not the timescale over which attributes or contextual factors become important. Arrows denote the influence of one factor on another, and the directionality (or bidirectionality) of this influence.

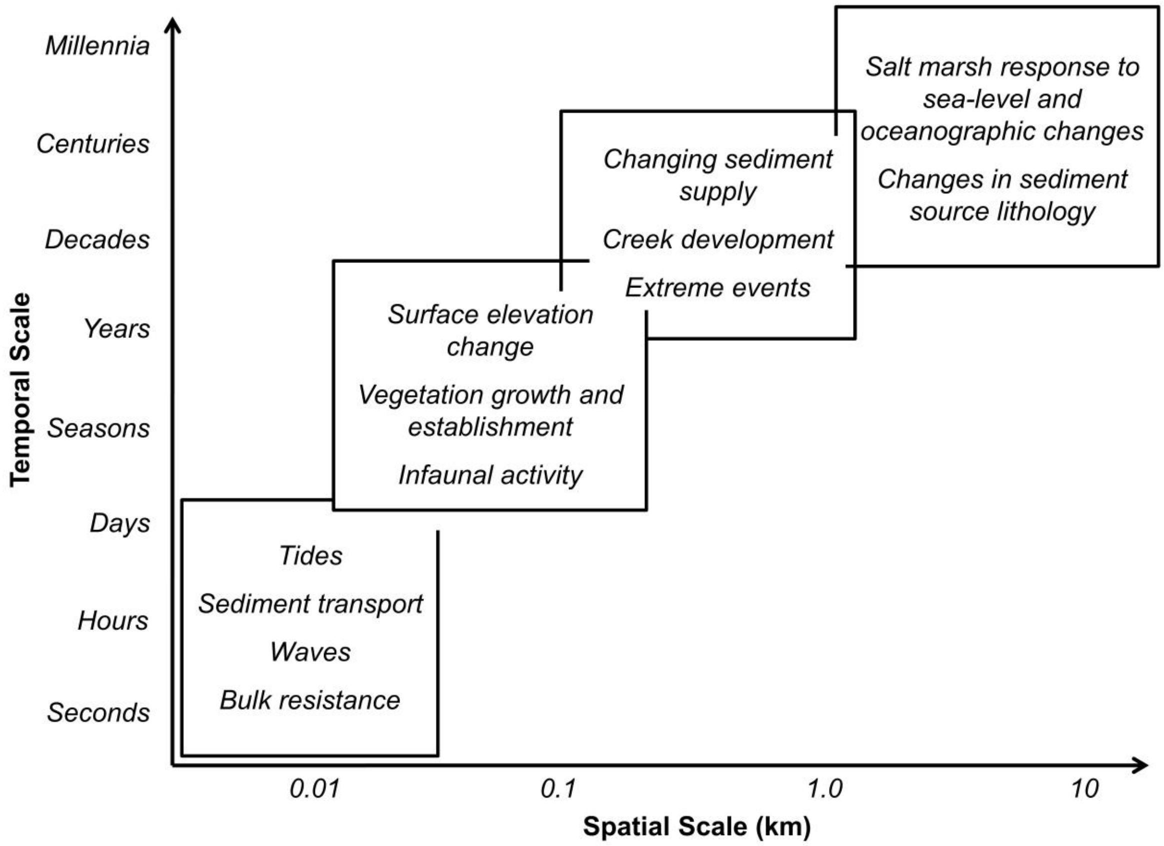

Figure 7: Spatial and temporal scales involved in salt marsh evolution, and thus substrate composition and properties. Modified from: Spencer & Moeller (2012), based on the original by Cowell & Thom (1994).

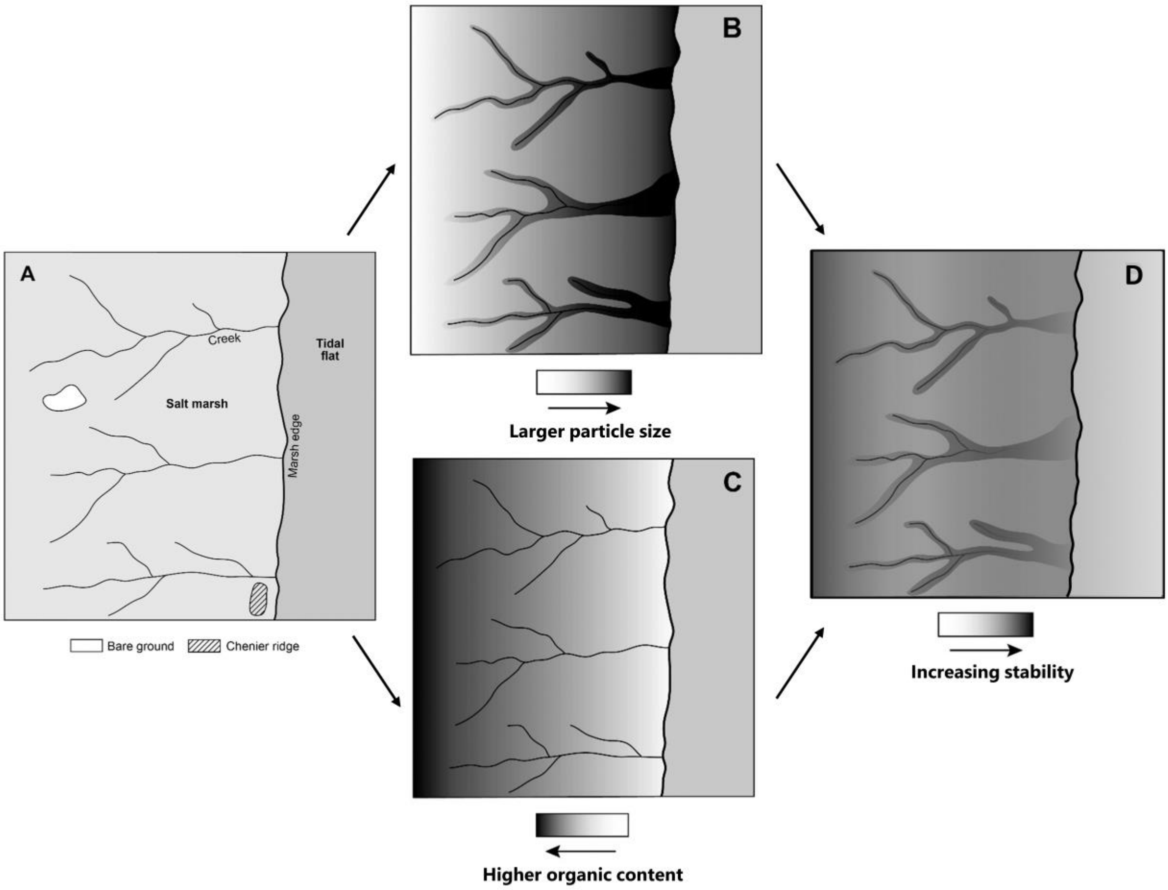

Figure 8: An example of an approach, in which a base layer of the marsh extent and features (A) is overlain by layers showing the within-marsh variation in substrate properties for a given marsh (B and C) to produce an overall map of marsh resistance (D).

Table 1: Overview of the direct effects of substrate properties on marsh stability and the settings in which these studies have been undertaken, based on marsh exposure and tidal range. Indirect effects (i.e. where a substrate properties influences another property or process, which then affects stability) were excluded.

Substrate property	**Effect on stability**	**Geographical location (marsh type-open coast/estuarine/back-barrier) and tidal range (micro/meso/macro/mega)**	**References**
Geochemistry	Greater interstitial phosphorous and inorganic nitrogen can increase decomposition rates	Northern Jutland, Denmark; fjord marshes	Mendelssohn et al. (1999)
	Soluble iron or aluminium can strengthen biofilms	Laboratory study Laboratory study	Stoodley et al. (2001) Möhle et al. (2007)
Clay mineralogy	Affects water retention and expansion upon wetting (which makes the substrate more erodible)	Essex, UK; macrotidal and Severn estuary, UK; megatidal	Crooks & Pye (2000)
Particle size	Finer cohesive sediments are less erodible	Dutch Wadden Sea; Man-made back-barrier marshes; mesotidal (tidal range 2.4 m) Galveston Island, Texas; back-barrier marsh; microtidal Essex, UK and Morecambe Bay, UK; open coast marshes; macrotidal Italian Northern Adriatic; lagoonal marshes; microtidal (65-80 cm tidal amplitude)	Houwing (1999) Feagin et al. (2009) Ford et al. (2016) Lo et al. (2017)
Bulk density	Higher bulk densities reduce erodibility	Essex, UK; Managed realignment site; estuarine marsh; macrotidal (mean tidal range 4.5 m) Conceptual framework	Watts et al. (2003) Winterwerp et al. (2012)
Organic content	Organic-rich substrates are less erodible	Essex, UK and Morecambe Bay, UK; open coast marshes; macrotidal Massachussetts, USA; micro/meso-tidal (2.7 m tidal range and 1.2 m tidal range)	Ford et al. (2016) Knott et al. (1987)
Salinity	More saline cohesive sediment is less erodible	Laboratory tests Westerschelde estuary, Netherlands and Humber estuary, UK	Parchure & Mehta (1985) Tolhurst et al. (2006)
Biofilm presence/ absence	Increased resistance to erosion in locations of EPS presence	Severn Estuary, UK; estuarine marsh; megatidal Sylt-Rømø Bight, Germany; back-barrier marsh; mesotidal Westerschelde estuary, Netherlands; mesotidal (mean tidal range 4 m) No field measurements Sediments from Eden estuary, Scotland, followed by lab analysis Modelling approach Jiangsu Province, China; macrotidal	Underwood & Paterson (1993) Tolhurst et al. (1999) Tolhurst et al. (2006) Le Hir et al. (2007) Tolhurst et al. (2008) Kakeh et al. (2016) Chen et al. (2017)
Vegetation canopy	Low density vegetation, or stiff stems can increase turbulence and scour	Laboratory study Galveston Island, Texas; back-barrier marsh; microtidal	Bouma et al. (2009) Feagin et al. (2009)
Root properties	Roots provide tensile strength and reduce surface or edge erodibility and marsh lateral erosion rates	Westerschelde,estuary, The Netherlands; estuarine marshes; macrotidal (spring tide range 4.4-5.5 m) Modelling study Beaulieu estuary, S England; estuarine marsh; mesotidal (mean spring tidal range 3.7 m) Plum Island estuary, Massachussetts, USA; estuarine/back-barrier marsh; mesotidal (mean tide range 2.9 m)	Van der Wal et al. (2008) Mariotti & Fagherazzi (2010) Chen et al. (2012) Deegan et al. (2012)

		Louisiana, Alabama and Mississippi, USA marshes; microtidal Venice Lagoon; lagoonal marsh; microtidal (tidal range ~60 cm) Northern Barataria Bay, Louisiana, USA; Northern Adriatic; lagoonal marshes; microtidal (average tidal amplitudes of 65-80 cm) Westerschelde estuary, The Netherlands; estuarine marshes; macrotidal; (spring tide range 4.4 - 5.5 m) Various Louisiana marshes	Silliman et al. (2016) Bendoni et al. (2016) Lin et al. (2016) Lo et al. (2017) Wang et al. (2017) Sasser et al. (2018)
Voids/ cracks/ subsurface stratigraphy	Tension cracks can instigate toppling failures	Venice Lagoon; lagoonal marshes; microtidal	Francalanci et al. (2013)
	Act as a lateral water pathway, along which the flow can erode	Modelling study Restored marshes, Blackwater estuary, UK; estuarine marshes; macrotidal	Xin et al. (2012) Tempest et al. (2015)

Salt marsh stability reflects, at least in part, the cumulative interaction of forcing and resistance over time. We review marsh resistance by outlining how substrate properties may affect marsh substrate stability, the spatial variation in these properties, and how they both affect, and are affected by, salt marsh processes. We then discuss how the cumulative impact of these interactions over annual-decadal timescales affects marsh stability.

Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing

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