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Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing

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Earth Surface Processes and Landforms

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 areas, 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 recreation schemes. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: salt marsh stability; erosion; substrate properties; process-based measurements; nature-based coastal protection

Introduction

The importance of marsh stability

Salt marshes are globally distributed, intertidal wetlands, occupying distinct elevation ranges that vary depending on tidal regime (Figure 1; Friess *et al.*, 2012). In northwest 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 United States, they can be found below mean sea level, through to the highest astronomical tide level (Figure 1). However, as salt marshes in northwest 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), colonized by halophytic vegetation, once a given elevation is reached (Allen, 2000; Huckle *et al.*, 2004).

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;

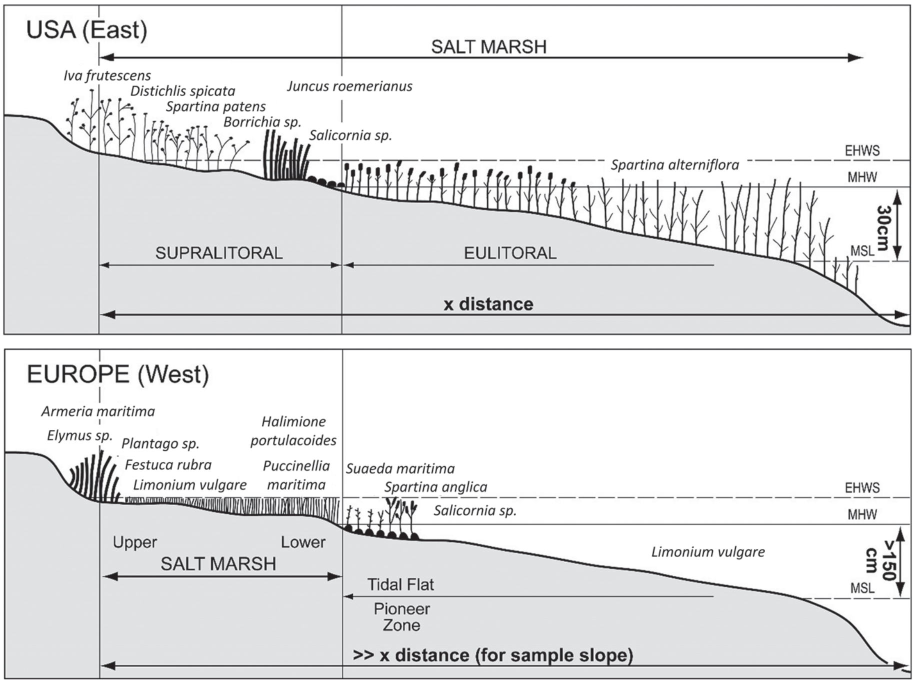

FIGURE 1. Comparison between northwest European marshes and those on the eastern coast of the United States. Modified from Dame and Lefeuvre (1994).

Spalding *et al.*, 2014). These include carbon sequestration (Rogers *et al.*, 2019), habitat provision (Spencer and Harvey, 2012) and pollutant immobilization (Crooks *et al.*, 2011). Salt marshes have an elevated position in the tidal frame and high surface roughness due to microtopographic 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 and Christie, 2018). This dissipation is an integral morphodynamic feedback, with co-adjustment of process and form (Figure 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).

Spalding *et al.* (2014) recognize that marshes can provide significant advantages over conventional hard engineering approaches in particular locations. This is both because of the range of the 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

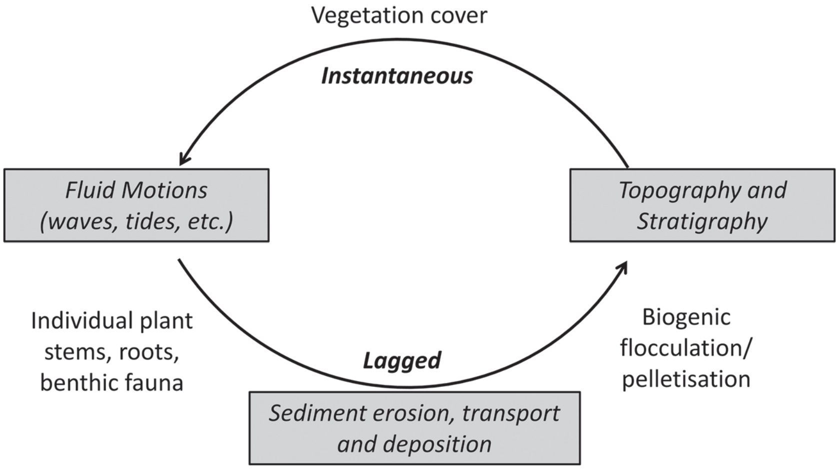

FIGURE 2. Morphodynamic feedbacks in salt marshes. Modified from Möller (2012).

dissection have been recorded on many of the world's shores (Cooper *et al.*, 2001; van der Wal and Pye, 2004; Baily and 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 United States (Leonardi and Fagherazzi, 2014, 2015) to more than 10 m per year, as reported, for example, for locations in the outer Thames Estuary (Greensmith and 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 have been shown to follow both linear (Marani *et al.*, 2011; Priestas *et al.*, 2015; Leonardi *et al.*, 2016; Finotello *et al.*, 2020) and power-law trends (Schwimmer, 2001; Mariotti and 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 and 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 over-riding properties affecting marsh substrate behaviour under the action of water, how these interact and how they may affect the dynamics of exposed substrates on the surface, at 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).

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 and 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, b). 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 (Figure 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 and at the scale of the entire soil matrix from the surface to well below the depth of the root zone. Finally, it is important to recognize 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).

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 depends on the species present (Figures 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.

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 (Figure 4; Chapman, 1960). Similarly, in Morecambe Bay

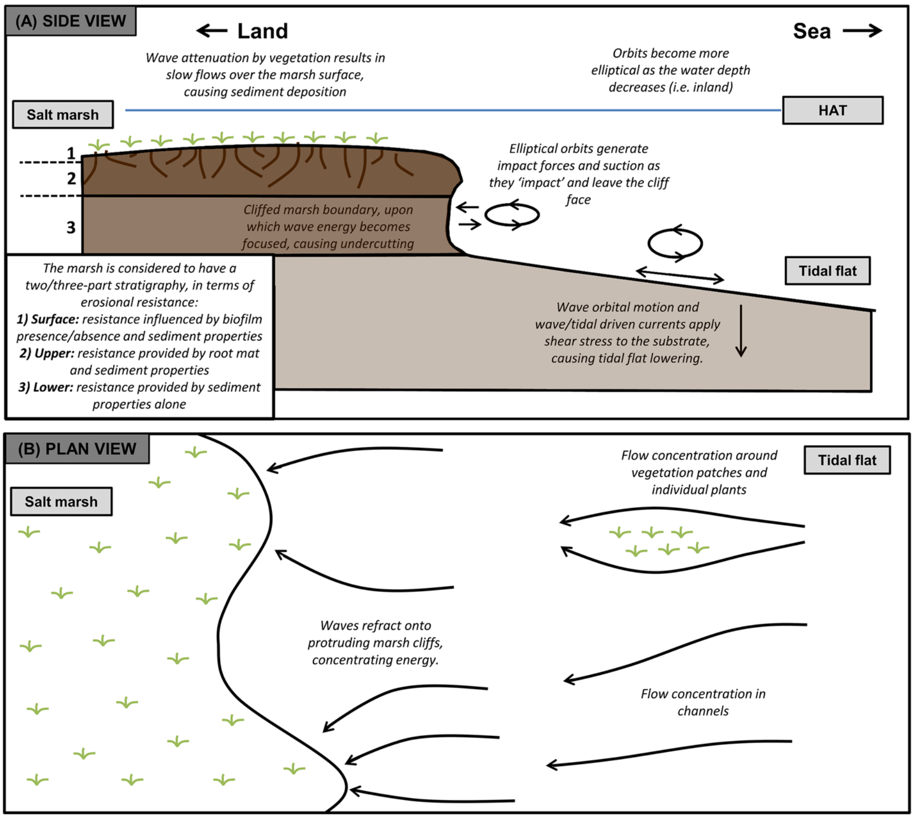

FIGURE 3. Hydrodynamic forcing on the tidal flat surface, marsh cliff and marsh surface in side view, using the example tidal level of highest astronomical tide (HAT) (a) and plan view (b). [Colour figure can be viewed at wileyonlinelibrary.com]

(UK), the common saltmarsh grass (*Puccinellia maritima*) provides much of the marsh surface strength by creating a dense root mat, which extends c. 14 cm below the surface, with tap roots extending deeper (Figure 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).

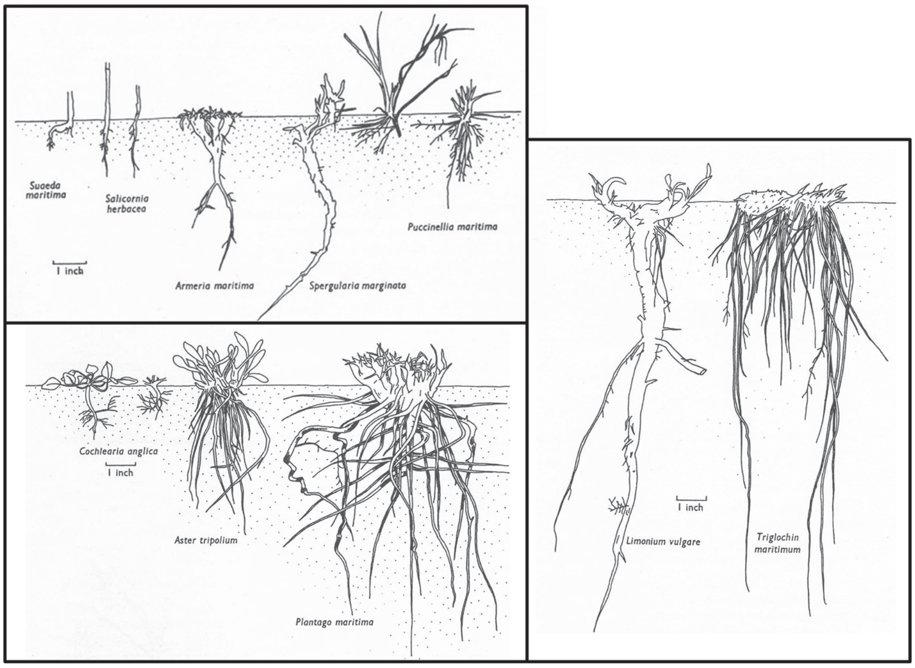

FIGURE 4. The varying lengths and structures of root systems for species from Plover Marsh, North Norfolk (UK) for species growing at 2.96 m ODN (as of 1934). One inch is approximately equal to 2.54 cm, therefore the *Limonium vulgare* root extends to approximately 25 cm depth. Taken from Chapman (1960, pp. 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 (UK) in July 2018. The knife in the photo is approximately 20 cm in length. [Colour figure can be viewed at wileyonlinelibrary.com]

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 and 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 and 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 10-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 in 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 and 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 mobilize the sediment into suspension (Fagherazzi *et al.*, 2006; Fagherazzi and 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 seasonal variability (Paul and Amos, 2011), but also the water level above the marsh surface (Möller *et al.*, 1999) and marsh edge morphology (cliffed vs. ramped; Möller and 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 (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 (Figure 3b).

Wave action also generates impact forces. These are particularly important at cliffed marsh edges (Mariotti and 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 and 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 United States (Leonardi and Fagherazzi, 2014). Such sediment removal may become the main marsh loss mechanism, as shown by modelling studies (van de Koppel *et al.*, 2005; Mariotti and Fagherazzi, 2013).

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. 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 and Paterson, 1997; Grabowski *et al.*, 2011). A summary of substrate properties and implications for substrate stability is provided in Table 1.

Chemical and physical sediment characteristics

Geochemical properties, such as clay mineralogy and water geochemistry, affect electrochemical particle attractions (Grabowski *et al.*, 2011). For example, smectites are the most electrochemically active mineral, followed by micas, then kaolinite (Grabowski *et al.*, 2011). Consequently, smectites can retain water and undergo considerable expansion upon wetting (Carr and 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 and Weil, 2002). However, this behaviour is also influenced by porewater salinity. Laboratory studies have found that more saline cohesive sediment is less erodible than that with lower salinity (Parchure and 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 and van Kesteren, 2004). Similarly, field work by Crooks and 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 and 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 and 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 and 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 sub-surface sediment compaction, root decomposition/growth and soil shrinkage (Cahoon, 2003, 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 (Figures 3 and 5). As such, processes of marsh formation that affect variability in sediment composition and structure may affect retreat that occurs decades or centuries later.

Organic content

The organic content of a marsh substrate represents both particulate organic carbon and roots (both live and partially decomposed). We focus on the latter later; this section looks at 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, the 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, Brain *et al.* (2011, 2015) found greater compression in sediments with higher OC and below-ground root content. These sediments tended to have high initial void 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 (Massey *et al.*, 2006). For example, under storm conditions in microtidal marshes in Louisiana, Florida and North Carolina (USA), 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 United States.

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 colonization and future organic matter content (Figure 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 (J. Bartholdy *et al.*, 2010b). 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

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's properties influence 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	Stoodley *et al.* (2001)
		Laboratory study	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 and Pye (2000)
Particle size	Finer cohesive sediments are less erodible	Dutch Wadden Sea; manmade back-barrier marshes; mesotidal (tidal range 2.4 m)	Houwing (1999)
		Galveston Island, TX; back-barrier marsh; microtidal	Feagin *et al.* (2009)
		Essex and Morecambe Bay (UK); open coast marshes; macrotidal	Ford *et al.* (2016)
		Italian Northern Adriatic; lagoonal marshes; microtidal (65–80 cm tidal amplitude)	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)	Watts *et al.* (2003)
		Conceptual framework	Winterwerp *et al.* (2012)
		Essex and Morecambe Bay (UK); open coast marshes; macrotidal	Ford *et al.* (2016)
Organic content	Organic-rich substrates are less erodible	Massachusetts (USA); micro/mesotidal (2.7 m tidal range and 1.2 m tidal range)	Knott *et al.* (1987)
Salinity	More saline cohesive sediment is less erodible	Laboratory tests	Parchure and Mehta (1985)
		Westerschelde Estuary (Netherlands) and Humber Estuary (UK)	Tolhurst *et al.* (2006)
Biofilm presence /absence	Increased resistance to erosion in locations of EPS presence	Severn Estuary (UK); estuarine marsh; megatidal	Underwood and Paterson (1993)
		Sylt-Rømø Bight (Germany); back-barrier marsh; mesotidal	Tolhurst *et al.* (1999)
		Westerschelde Estuary (Netherlands); mesotidal (mean tidal range 4 m)	Tolhurst *et al.* (2006)
		No field measurements	Le Hir *et al.* (2007)
		Sediments from Eden Estuary (Scotland), followed by laboratory analysis	Tolhurst *et al.* (2008)
		Modelling approach	Kakeh *et al.* (2016)
		Jiangsu Province (China); macrotidal	Chen *et al.* (2017)
Vegetation canopy	Low-density vegetation or stiff stems can increase turbulence and scour	Laboratory study	Bouma *et al.* (2009)
		Galveston Island, TX; back-barrier marsh; microtidal	Feagin *et al.* (2009)
Root properties	Roots provide tensile strength and reduce surface or edge erodibility and marsh lateral erosion rates	Westerschelde Estuary (Netherlands); estuarine marshes; macrotidal (spring tide range 4.4–5.5 m)	Van der Wal *et al.* (2008)
		Modelling study	Mariotti and Fagherazzi (2010)
		Beaulieu Estuary (south England); estuarine marsh; mesotidal (mean spring tidal range 3.7 m)	Chen *et al.* (2012)
		Plum Island Estuary, MA (USA); estuarine/back-barrier marsh; mesotidal (mean tide range 2.9 m)	Deegan *et al.* (2012)
		Louisiana, Alabama and Mississippi (USA) marshes; microtidal	Silliman *et al.* (2016)
		Venice Lagoon; lagoonal marsh; microtidal (tidal range ~60 cm)	Bendoni *et al.* (2016)
		Northern Barataria Bay, LA	Lin *et al.* (2016)
		Northern Adriatic; lagoonal marshes; microtidal (average tidal amplitudes of 65–80 cm)	Lo *et al.* (2017)
		Westerschelde Estuary (Netherlands); estuarine marshes; macrotidal (spring tide range 4.4–5.5 m)	Wang *et al.* (2017)
		Various	
		Louisiana marshes	Sasser *et al.* (2018)

(*Continues*)

Table 1. (Continued)

Substrate property	Effect on stability	Geographical location (marsh type – open coast/estuarine/back-barrier) and tidal range (micro/meso/macro/mega)	References
Voids/cracks/sub-surface 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.* (2015a, b)

susceptible to erosion (van der Wal and 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.

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 (J. Bartholdy *et al.*, 2010b). This reflected the distance to sediment source (marsh edge or second-order creeks; A. T. Bartholdy *et al.*, 2010a). As such, bulk density falls with distance from the creek (Kim *et al.*, 2013). Bradley and Morris (1990) found that compressibility was greater near the creek bank at two southeastern US sites. At these sites, substrates were characterized 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 interdependent, 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 (Figure 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

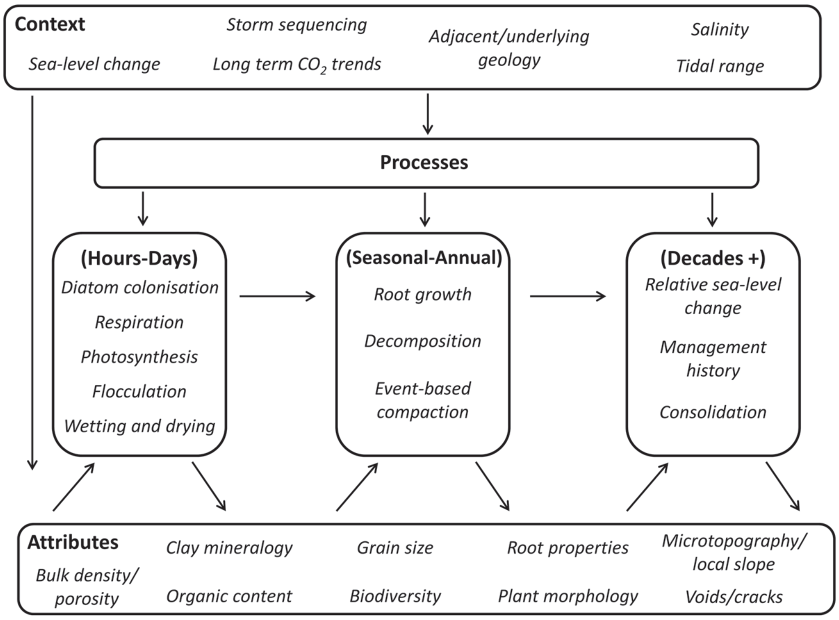

FIGURE 6. The cumulative impact of a suite of processes, attributes (marsh/tidal flat properties) and contextual factors (external influences on the system) that affect the stability of a sub-metre block of marsh substrate at a given point in space and time. The timescale bar relates to the timescale over which the processes operate (hours to 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.

slowly (Wagner *et al.*, 2017). As an open structure of salt marsh sediments is known to be less erodible 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.

Salinity

On an inter-particle scale, higher salinity promotes flocculation as sodium ions neutralize 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, 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 below-ground root production was greater in high-salinity marshes on Long Island, NY. 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).

Presence of extracellular polymeric substances

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 stabilizing 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 stabilizing 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, 2006b). Given that microbiological assemblages preferentially colonize fine-grained (clay/silt-dominated) sediments (Dyer *et al.*, 2000), EPS presence can further amplify the higher erosion resistance of finer-grained sediments.

On tidal flats, this stabilizing effect of EPS was originally thought to be short-lived so, following biofilm erosion (during high shear stress; Fagherazzi and 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 stabilizes 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 2 min during a 17-min 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 colonize the substrate, so biofilm influence is greatest in late spring and summer, but can be negligible in winter (Underwood and 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 (see 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 on EPS in 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 biostabilization, see Paterson *et al.* (2018).

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 stabilize sediment, prevent surface erosion and reduce boundary-layer water velocities and thus hydrodynamic energy.

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 destabilize surface sediment directly (Spencer and Möller, 2012), 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, below-ground 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 and Fagherazzi, 2010), and roots have been recognized as important for reducing erodibility and thus marsh lateral erosion rates (Lin *et al.*, 2016; Silliman *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 above-ground biomass reduces the wave attenuation capacity. As a consequence, incident hydrodynamic energy may be higher (Schoutens *et al.*, 2019). However, the role of below-ground roots for marsh stability will partly depend on the species, and root structures, present (Figure 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 and Li, 2011) and reinforce the soil matrix by providing tensile strength (Gray and 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), producing root exudates which bind the soil (Jones *et al.*, 2009) and increasing substrate particulate OC which in turn increases soil structural integrity (Bronick and 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 and Poesen, 2010; Knapen and 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 and Collison, 2002). Tensile strength provided by roots varies seasonally, being highest in the summer months (Morris and 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 and 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 below-ground 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 stabilizing 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 localized 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 stabilizing 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 below-ground 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 Figure 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 colonized by certain species (e.g. the woody shrub sea purslane, *Atriplex portulacoides*) are more resistant to flow-induced erosion, while those colonized by other species (e.g. the sea rush, *Juncus maritimus*) provide greater resistance to mass movement. Using micro-CT scanning to characterize the root structure at the same site in southern England, Chen *et al.* (2019) inferred that the fine, but dense, root mat provided by *A. 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 stabilizing effect on cohesive sediments, but this stabilizing effect also depends on the substrate composition (and thus consolidation). Again, this demonstrates the complex links between various substrate components (see Figure 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 previously, 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 (Figure 6).

Deeper sub-surface 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 characterized 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.

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 sub-surface 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 (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-destabilizing’ 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 have been correlated with inter-annual changes in these ‘bio-destabilizing’ biota (Widdows and 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 oxidized conditions in the upper 10–15 cm of a *Spartina alterniflora*-dominated marsh in South Carolina (USA), thus allowing decomposition of below-ground biomass, which lowered the substrate shear strength (Wilson *et al.*, 2012). Therefore, bioturbation can increase porosity and reduce below-ground live biomass and bulk density, which reduces substrate strength. However, as invertebrates generally colonize 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 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 Figure 6).

Biological activity (e.g. crabs, ragworms and amphipods) can increase sediment susceptibility to erosion by waves/tides and can reorganize 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 and Paramor, 2004; Paramor and Hughes, 2004), however this argument has been questioned due to a lack of procedural control (Wolters *et al.*, 2005).

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 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 below-ground biomass (Elschot *et al.*, 2015), which can increase stability. 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).

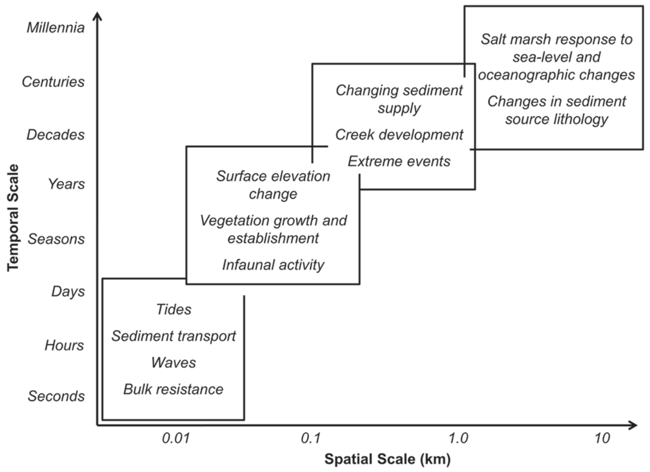

FIGURE 7. Spatial and temporal scales involved in salt marsh evolution, and thus substrate composition and properties. Modified from Spencer and Moeller (2012), based on the original by Cowell and Thom (1994).

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 (Figure 2), as well as the complex interactions between substrate properties, become important (Figure 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 inter-relationships and (c) the morphodynamic feedback that connects substrate formation to landform evolution and vice versa.

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 inter-relationships 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 inter-relationships 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. As yet, little is 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 (Figure 6). A better understanding of within-marsh spatial variability in substrate properties and their

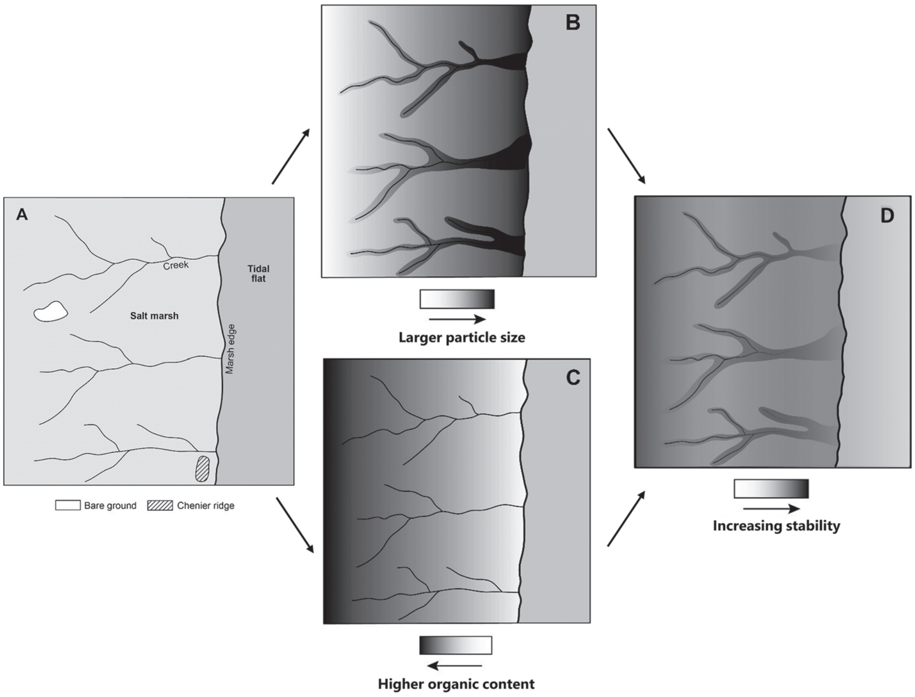

FIGURE 8. An example of an approach in which a base layer of the marsh extent and features (A) is overlain by layers showing the within-marsh variation in substrate properties for a given marsh (B, C) to produce an overall map of marsh resistance (D).

interactions may allow us to derive 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.

Figure 8 illustrates schematically how two or more parameters could be combined into such an index. Figure 8a depicts a hypothetical marsh platform with multiple bifurcating channel (creek) networks, interior bare ground and marsh margin shell sand (chenier) ridges. Figure 8b shows how particle size varies within a marsh, with larger particles near the creek edges and marsh edge. Figure 8c shows how organic content increases with elevation. Similar layers for other substrate properties could be produced, and converted into weightings across the layer to summarize 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 (Figure 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.

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. Figure 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 (Figure 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 content, etc. All of these properties have been shown to relate to substrate resistance to hydrodynamic forcing (Figure 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 (Figure 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 recognized 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).

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 localized with individual patches of higher resistance less than metres 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 and Tucker, 1975; Visser *et al.*, 2000; Hawkes and 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.

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 and Priestas, 2010; Fagherazzi *et al.*, 2013; Schuerch *et al.*, 2019). Given identical forcing conditions, the evolution of the marsh over longer (annual to decadal) timescales 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 and 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 and 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 and 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 Figure 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, 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 and Carr, 2014). In van de Koppel *et al.*'s (2005) 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 parameterize the properties identified above as influencing rates and location of erosion.

Marsh edge retreat may also represent a form of 'self-organization' 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 (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 to metre scales.

This paper 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 inter-relationships 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 to centuries). In practice, this increased understanding will both improve projections of future marsh extent and have key implications for the success of future salt marsh restoration and recreation (e.g. in 'managed realignment') schemes. Such schemes are becoming increasingly popular for sustainable flood risk management and habitat creation, particularly in Europe (Esteves and 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 the 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 timescales.

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. However, less is 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 Figure 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 and 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 covariance between properties as well as their combined influence on substrate stability (Figure 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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Data Availability Statement

Data sharing is not applicable to this paper as no new data were created or analysed in this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

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