# Morphodynamics of salt marshes in a period of accelerated sea level rise.

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**Key points:**

1) Vertical and horizontal dynamics must be combined to understand salt marsh evolution
2) A sediment budget and is the key variable to measure marsh resilience to sea level rise
3) Remote sensing will provide spatially distributed datasets to inform a new generation of numerical models of salt marsh evolution

**Abstract**

Salt marshes are dynamic systems able to track sea level by vertically accreting or laterally expanding and contracting. Yet many processes driving marsh evolution are still poorly understood. Here we present the grand challenges we need to address to fully characterize marsh morphodynamics. Without predictive models of marsh evolution we will be unable to determine the long-term marsh evolution. Both horizontal and vertical dynamics must be resolved. Vertically the marsh has to accumulate enough material to contrast rising water levels. Horizontally marsh erosion at the ocean side must be compensated by landward expansion in forests, lawns and agricultural fields. The variety of marsh plants and their interactions with hydrodynamics and sediment transport need also to be fully captured. We advocate that a sediment budget resolving all the sediment fluxes in a marsh complex is the most important metric of marsh resilience. Characterization of these fluxes will allow to connect salt marshes to other landforms and to unravel feedbacks controlling the evolution of the entire coastal system. Remote sensing and high resolution computer models are instrumental in determining salt marsh resilience. Novel remote sensing techniques will provide spatially distributed datasets that will inform a new generation of computer models. These models will be able to determine the fate of salt marshes in a period of accelerated sea level rise.

## 1. Dynamic salt marshes in a changing environment

Salt marshes develop in the presence of favorable conditions for plant growth and sufficient sediment supply (e.g. Bakker and Vries, 1992; Fagherazzi et al., 2012; Ganju et al., 2015). Once established, vegetation can accumulate extensive amounts of sediments which promote the formation of a marsh platform the stability of which is increased by the shear strength of plants roots (e.g. De Battisti et al., 2019). Salt marshes represent areas of high biological productivity providing a natural barrier against the effects of sea level rise and storms (Langley et al., 2009, Smith et al., 2015). Additionally, they protect coastal zones through their aptitude to grow in elevation trapping and locally generating sediments.

There is evidence that salt marshes will significantly diminish their extension under current estimates of sea level rise (Alizad et al., 2016). Coastal wetlands evolution includes a combination of ecological and physical processes involving sediment erosion and deposition. In particular, sediment deposition rates on marsh platforms are largely controlled by the duration and frequency of tidal flooding (Schuerch et al., 2018). Sediment deposition and organic matter accumulation must match sea level rise otherwise the marsh will drown (Reed 1995). Subsidence induced by compaction of the soft marsh substrate exacerbates the vulnerability of these delicate ecosystems (Cahoon et al., 1995). Salt marshes can also erode laterally at the water boundary due to waves and storms, and transgress on the mainland because of sea level rise (Figure 1). Only the full understanding of both vertical and horizontal dynamics will enable us to determine the fate of salt marshes in a period of accelerated sea level rise.

Physical processes mediated by biology are the main drivers of marsh evolution (Fagherazzi et al. 2012). Therefore quantitative models of marsh physics are critical to forecast the fate of these delicate environments. In this review we will focus on the grand challenges we face to fully capture the physics of salt marshes with conceptual and computer-based models. The main obstacle in our ability to forecast the long-term evolution of salt marshes is the absence of spatially distributed datasets that inform us about the complexity of this important environment. Remote sensing will play a major role in salt marsh studies in the near future, providing critical information and data nowadays still missing (Figure 1).

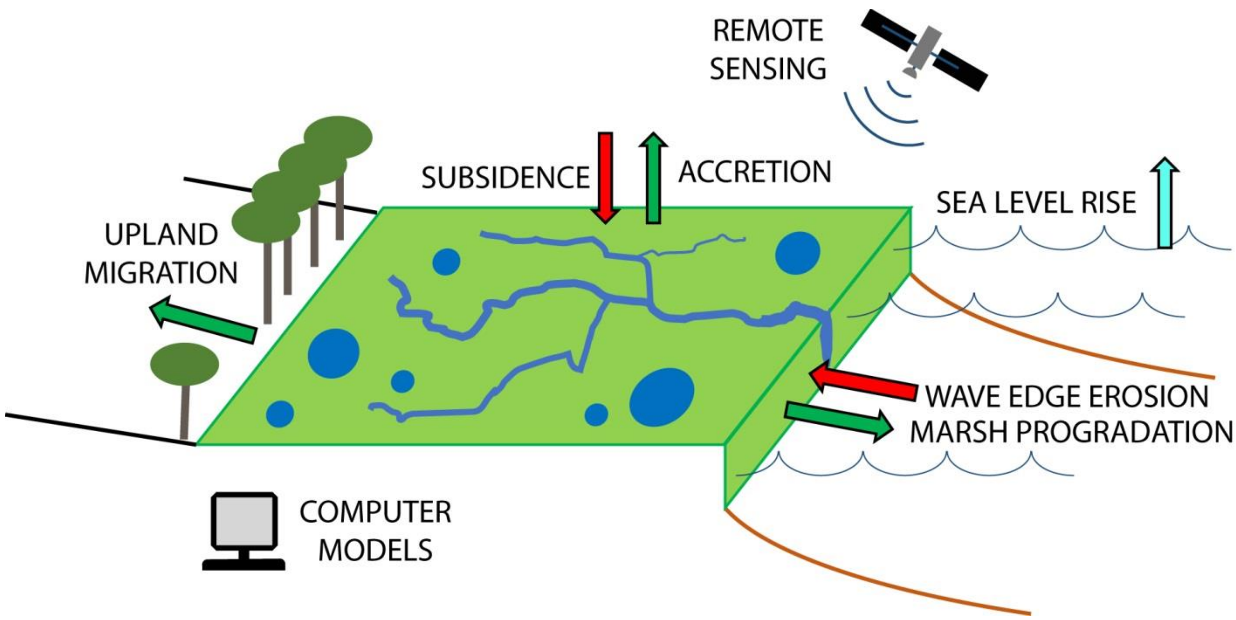


**Figure 1**. Marsh evolution under sea level rise. Computer models and remote sensing will play a critical role to forecast the fate of these landforms in the next century.

## 2. Salt marshes and sea level rise

The key question about salt marshes is whether they will survive sea level rise. To address this overarching question we need to develop physically-based models that capture the chief processes regulating the vertical dynamics of the system. The simplest framework to study marsh evolution considers 0-D models (also called point models), which simulate the competition between vertical accretion and Relative Sea Level Rise (RSLR) (Allen 1990; Kirwan et al., 2010; Morris et al., 2002). Accretion includes both organic and inorganic material while RSLR is the sum of eustatic sea level rise and subsidence. Despite the simplicity of this framework, challenges are present in measuring and modeling its various components.

For the organic fraction, a major challenge is determining how much of the organic material is conserved (as opposed to being consumed) through time. For example, an open question is whether the labile component of the organic matter is preserved if sediments are buried quickly and thus isolated from oxygen (Unger et al., 2016). Most of the volume accreted by the organic matter is constituted by porespace (Morris et al., 2016). Thus, from an accretion point of view, predicting the porespace volume might be as important as predicting the amount of organic matter. Other challenges include predicting how organic matter production and decomposition will change as a function of climatic (Crosby et al., 2017; Kirwan and Mudd, 2012) and human-driven (Elsey-Quirk et al., 2019a) modifications of temperature, rainfall, salinity, and nutrients. Advances in this area will likely come from field and laboratory experiments, and from integrating this information into usable models.

For the inorganic sediment, challenges remain in quantifying the sediment supply; specifically the suspended sediment concentration that drives deposition. Several widely used models such as SLAMM (Lee II et al., 2014) and HydroMEM (Alizad et al., 2016) assume that sediment concentration is spatially uniform, while in reality it is known to be highly variable in space. Simple formulations can be introduced to describe spatial patterns of suspended sediment concentration, e.g., the decrease from the channels toward the marsh interior (Kirwan et al., 2016b). This task becomes more complex if the sediment supplied to the marsh is required to stem from a mass balance, i.e., if it is calculated by solving the equations for sediment erosion, transport, and deposition (Mariotti, 2018; Ratliff et al., 2015). In this case fully explicit models are deemed necessary. The other challenge is accounting for temporal variability, e.g., high suspended sediment concentrations during energetic events (Schuerch et al., 2019), which leads to episodic vertical accretion (Goodwin and Mudd, 2019; Reed, 1989). Models for marsh evolution can easily simulate temporal variability, even though they often face the problem of satisfying mass conservation. Field measurements of suspended sediment concentration at multiple locations for long periods of time (i.e., years) – a technically feasible but costly endeavor – are needed to provide reliable constraints on sediment supply to the marsh (Ganju et al. 2015). Eustatic sea level rise is relying on outputs from climate models or paleoclimate studies. Models need to include probabilistic inputs of RSLR, given the uncertainty in the forecast of future sea levels (Rahmstorf 2010).

Subsidence is a particularly challenging and a relatively unconstrained process. Subsidence is generally divided into deep and shallow (Jankowski et al. 2017). The latter is limited to a depth of few meters and includes hydrological alterations (e.g., drained soil due to marsh ditching), which might accelerate carbon oxidation and soil compaction. Because subsidence is weakly dependent on short-term marsh processes, it is generally simulated as a boundary condition in salt marsh models. Explicitly accounting for subsidence in a process-based manner might be opportune when considering long time scales (at the scales of evolution of bays and deltas and their wetlands). New methods to analyze data, e.g., machine learning, could be highly efficient. Also, extensive networks of Surface Elevation Tables (SETs) are shedding light on the spatial variability of subsidence (Webb et al. 2013).

Problems emerge when the distinction between processes is not as clear as described above. It is well established that the organic and inorganic sediments deposited on the surface experience subsidence and compaction (which here is assumed to also include organic matter degradation) as they get buried through time. One approach is to consider the gross sediment accumulation at the surface and separately include all the processes that lead to subsidence into the RSLR term. Another approach is to consider a net vertical accretion, in which some of the initial subsidence is directly subtracted from the gross accretion, while the compaction occurring at later time (deeper layers) is considered separately. The accretion that does not include compaction is often referred to as short-term accretion, while the accretion that includes some of the initial subsidence is referred to as long-term accretion. A continuum of approaches is present in the scientific community, in which different amount of subsidence is included in the net accumulation term as opposed to the RSLR term. This choice depends on the time scale considered – the longer the time scale, the larger the effects of compaction and subsidence are – an uncertainty that has brought about a vivid discussion (Kirwan et al., 2016a; Parkinson et al., 2017).

## 3. Are salt marshes drowning?

A relevant question is whether salt marshes are keeping pace with RSLR or whether they are drowning. Surprisingly, contrasting conclusions are inferred depending on the framework in which the data are analyzed. Several studies directly compare vertical accretion with RSLR and determine whether marshes are keeping pace (e.g. Crosby et al., 2016). This straightforward approach does not take into account the feedbacks between marsh inundation (hydroperiod) and vertical accretion (Kirwan et al., 2016a). Measuring an accretion rate lower than RSLR in a regime of accelerated SLR might simply indicate that marshes are approaching a lower elevation that will enable a faster accretion by both organic and inorganic sediment.

If ecogeomorphological feedbacks (i.e., the increase in accretion with inundation) are taken into account, marsh drowning is only predicted when the maximum vertical accretion rate is lower than the rate of RLSR (Kirwan et al., 2010). When the maximum accretion is lower than the maximum value, the initial marsh elevation (also call the “elevation capital”) will determine the time before drowning. If the suspended sediment concentration is assumed to be spatially uniform, this approach predicts that the low marsh will drown before the high marsh (Alizad et al., 2016).

The simplicity of this vertical approach has made it very common, especially in coarse-resolution global assessment of marsh evolution (Schuerch et al., 2018). One important caveat of this approach, however, is that marshes accreting at the same rate of RSLR are not necessarily maintaining their areal extent through time. Indeed, horizontal processes such as marsh edge retreat (Mariotti and Fagherazzi, 2010) and channel widening (Deegan et al., 2012; Mariotti, 2018; Watson et al., 2016) could erode marshes independently of their vertical accretion. Furthermore, the formation and enlargement of ponds could cause marsh loss despite the vegetated marsh platform keeping pace with RSLR (Mariotti, 2016). Thus, focusing only on vertical accretion thresholds (Schuerch et al., 2018) could underestimate global marsh vulnerability to RSLR.

## 4. Lateral erosion and progradation of salt marshes

Salt marshes are dynamic landforms and their seaward boundary can significantly move over time. Salt marshes can undergo cyclic periods of expansion and contraction over time scales of decades to century (e.g. Allen, 2000). The retreat or prograding of marsh boundaries is regulated by both exogenous processes such as sea-level rise and wave energy and endogenous processes such as internal geo-technical processes. The presence of endogenous mechanisms is suggested by the observed occurrence of simultaneous cliff erosion and vegetation regrowth in front of marsh edges (e.g. van de Koppel et al., 2004; Leonardi et al., 2018).

Cyclic accretion and erosional trends have been recorded in several areas around the world. For instance, observations of salt marshes in Morecambe Bay, UK, have been indicating clear accretion and erosional cycles since the 19th century with spatial and temporal variability depending on the movements of nearby channels (Pringle, 1995). Stratigraphic analyses and carbon dating have suggested that many salt marshes in North America might have been rapidly expanding during the 18th and 19th century due to increased deforestation caused by European settlement and increased sediments delivery to the coastline (Pasternack et al. 2001). More recent observations of marsh degradation suggest the possible tendency of North America's marshes to return to pre-anthropogenic conditions (Kirwan et al., 2011). Except in few cases, we still do not know why salt marshes formed in many areas along the shore. If we do not understand the mechanics of marsh formation we cannot correctly plan marsh conservation and restoration projects. If in fact the conditions for marsh establishment and survival are not met, these projects are likely to fail in the long term. Unfortunately, areas where salt marshes are expanding are scarce, so we need to resort to detailed geological studies to understand the history of marsh establishment and evolution (e.g. Gunnell et al., 2013).

The erosion of salt marshes can follow different styles such as root-scalping, undercutting of the edge below the vegetation root-mat and associated cantilever failures and toppling (McLoughlin et al., 2015; Priestas et al., 2015). When waves occur with water elevations near the marsh platform, they can strike against the weak boundary separating the live vegetation root layer from the peat layer and this can cause erosion below the root-mat. The action of waves at marsh boundaries increases with the water level up to the point when the marsh is submerged.

Once the marsh is submerged, wave energy is dissipated due to wave breaking and vegetation friction, and the impact of waves at the boundary decreases (Tonelli et al., 2010; Leonardi et al., 2016). Undercutting is more common for salt marshes with a pronounced marsh edge; root scalping requires water levels to overtop the marsh and generally occurs during high surge levels or for marsh edges with a low slope (Priestas et al., 2015).

Van de Koppel et al., (2004) suggested that, during the early stages of marsh development, the interaction between sedimentation and plant growth creates a marsh platform and that the edge of the platform steepens as the marsh progrades. As a consequence of this steepening, the edge between the vegetated and un-vegetated platform becomes increasingly unstable. This leads to vegetation collapse, marsh edge retreat and landward migration of the boundary. In this sense, marsh retreat can be seen as an endogeneous process possibly leading to self-organization. The presence of self-organizing patterns for salt marshes has been also suggested by Leonardi and Fagherazzi (2014) within the context of eroding marsh edges. They suggested that a critical state for marsh boundaries is connected to the non-homogeneity of salt marshes and to the variability in erosional resistance along their boundaries. The critical state is the one promoting the erosion of weak marsh sites and consequent exposure of more resistant and uniform marsh portions, thus leading to an “armouring” of the marsh boundaries. When salt marshes approach self-organized criticality, erosion becomes unpredictable with low erosion rates characterizing the majority of the boundary but with occasional failures of large marsh portions. From a morphological point of view, self-organization results in a jagged boundary profile when the marsh is subject to low wave energy and a uniform and smooth marsh boundary in case of high wave energy and high average erosion rates. It has been thus suggested that the shape of the marsh boundary could be used as a tool to evaluate the state of vulnerability of salt marshes (Leonardi and Fagherazzi, 2015; Leonardi et al., 2016b).

The main challenge in estimating lateral erosions of marshes is the lack of geotechnical data. Few studies have empirically explored how differences in soil properties and vegetation control scarp erosion (e.g. Feagin et al. 2009), but we still lack spatially distributed geotechnical data to apply these findings at the landscape level. The mechanics of marsh erosion is also poorly understood, and only recently physically-based geotechnical models were developed in the laboratory (Francalaci et al. 2013, Bendoni et al. 2014). The challenge is to apply such theoretical frameworks in the field and at a large spatial scale.

Recent manipulative experiments have investigated the processes triggering the initiation of marsh boundaries migration (Bouma et al., 2016). Bouma et al., (2016) suggest that the passage from a stable to a prograding or eroding condition might be related to short-term fluctuations in sediment dynamics and bed elevation. Specifically, lateral erosion is triggered when short-term sediment dynamics create a significant height difference between marsh areas and surrounding tidal flats. Short-term sediment dynamics can also cause bed level changes which are too high to allow seedling establishment and associated marsh progradation. In fact seedling cannot survive if erosion exceeds a critical threshold causing uprooting, or if high deposition rates bury them too deeply (Bouma et al., 2016).

Once the marsh starts to erode, the onset of a new accretion cycle might be related to tidal flat dynamics and local sediment budgets. Field measurements show that the amplitude of short-term erosion and accretion rates along the tidal flat increases seaward and chances of accretion and seedling establishment are higher for locations closer to the coastline (Bouma et al., 2016). Therefore, chances of establishment might gradually increase as the marsh erodes.

The onset for marsh progradation could be related to a condition of low sediment reworking rates (absence of high bed level fluctuations causing seed burial or removal) and high sediments abundance (which can be regularly trapped by emergent vegetation and promote accretion). While reworking rates should be low to avoid burial or scour, the availability of sediments might be pivotal to promote accretion rates. Based on this, and on the fact that the onset for erosion can be related to steepening marsh edges, we suggest that low accretion rates and slowly prograding marsh boundaries which occupy large longitudinal portions of the shoreline, might be, in the long term, more stable than those marshes which are very rapidly expanding. The incorporation of these feedbacks between vegetation, erosion, and progradation in conceptual and numerical models of marsh evolution represents a clear challenge to be addressed in the near future.

Wind waves triggered by storms have been found to be an important contributor to salt marsh erosion (e.g. Möller, 2006;  Leonardi et al., 2016a; Leonardi et al., 2018). Schwimmer (2001) has been among the first to suggest the existence of a relationship between wave energy and marsh erosion. Marani et al. (2011) corroborated Schwimmer (2001) results using a non-dimensional analysis, observations from the Venice Lagoon, and literature data to illustrate the existence of a linear relationship between wave power and marsh retreat. Based on a dataset of erosion and wave climate from eight study sites around the world, Leonardi et al. (2016b) further showed that the response of salt marshes to increasing wave energy remains linear as the wave power increases and that there is not a critical threshold above which marsh erosion drastically increases. Furthermore, on the basis of a geomorphic work analysis, it was shown that given their relative low frequency, violent storms and hurricanes contribute little to the long-term erosion of salt marshes. In contrast, moderate storms with a return period of few months are those causing the most salt marsh deterioration (Leonardi et al., 2016b, Figure 1). As climate changes, the frequency and intensity of storms will be affected (Knutson et al., 2010). There is therefore a need to understand whether these variations in storminess will increase marsh erosion.

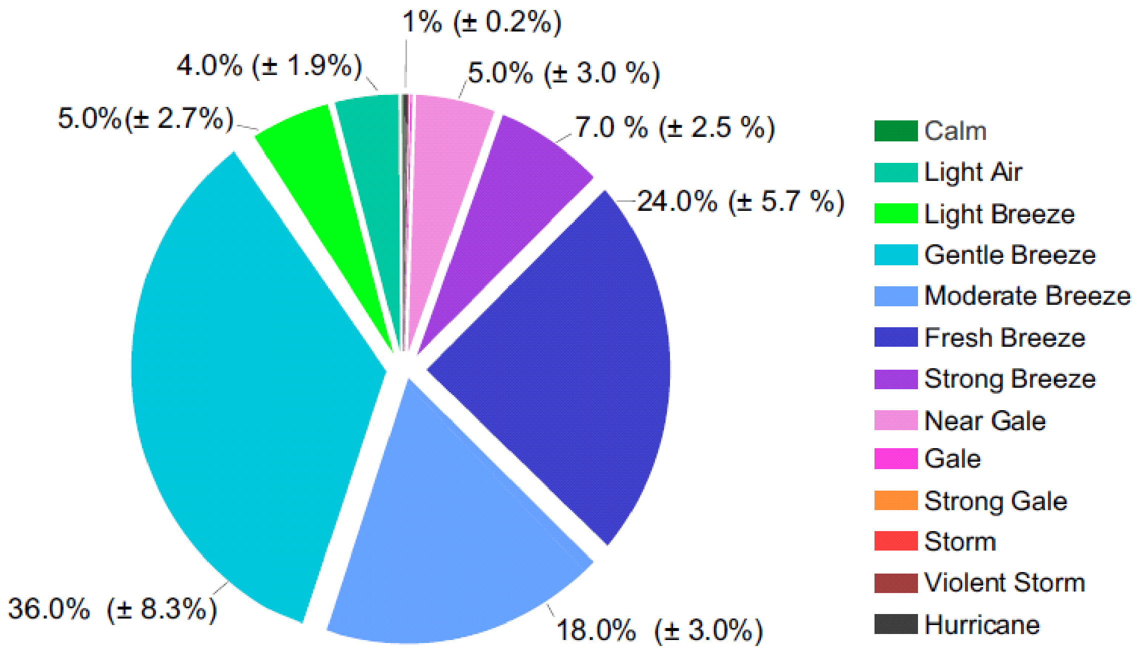


**Figure 2**. Average contribution of different wind categories to salt marsh erosion rates. Most of the erosion occurs during frequent, medium storms (return period around 3 months). As climate changes, the frequency and magnitude of storms will vary, affecting marsh erosion.

## 5. Will sea level rise affect marsh edge retreat?

SLR can affect marsh edge retreat through two mechanisms. The first mechanism is based on hydrodynamic considerations: if tidal flats surrounding a salt marsh accretes slower than the rate of RLSR they will deepen, promoting larger waves, and thus increasing marsh edge retreat (Mariotti et al., 2010). The second mechanism stems from a mass balance. Both marsh and mudflat need to trap sediments in order to maintain their relative elevation in a period of accelerated sea level rise. If there is not enough sediment import from outside the system, sediment can be released from the retreat of the whole edge-mudflat profile (Fig. 3). This is analogous to the Bruun model for the response of the shoreface to sea level rise, in which a faster vertical accretion triggers a faster retreat.

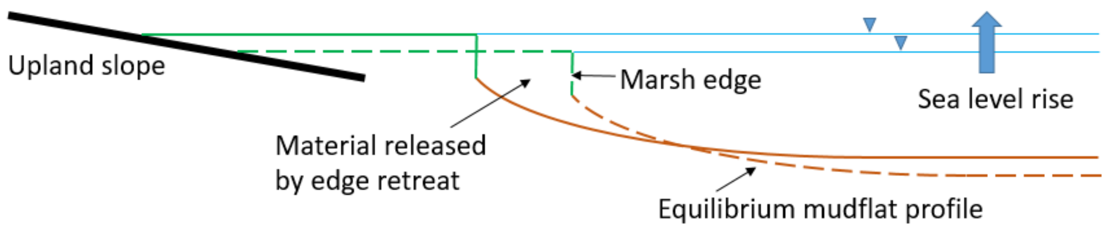


**Figure 3**. Bruun Rule applied to marsh edge retreat. This conceptual model is based on conservation of mass.

In numerical models of marsh evolution, this effect could be recreated by controlling the rate of marsh progradation. Marsh progradation is an artificial construct used to represent a process (the mudflat accreting and becoming a vegetated marsh) that is inherently vertical. Because this process tends to occur over a relatively short distance in front of the marsh edge, it can be thought as a lateral process. In a simple model (Mariotti and Carr, 2014), marsh progradation was related to the sediment concentration in the mudflats, and thus marsh progradation can only be reduced by processes that decrease this concentration (e.g., a relative deepening of the mudflat). This sediment concentration was not calculated in a way that conserves mass (e.g., the requirement of a larger sediment deposition did not affect the available suspended sediment concentration). A model that solved the mass balance and included both vertical mudflat changes and edge retreat showed indeed that marsh edge retreat increases with the rate of relative sea level rise (Mariotti and Canestrelli, 2017). This was also present in the 1D transect model of Mariotti and Fagherazzi (2010), in which the profile in front of the marsh becames steeper for larger rates of RSLR, i.e., reflecting a sediment starvation condition.

Whether the rate of marsh edge retreat has increased in the last decades because of the increased RSLR remains an open question. Measurements at the Virginia Coast Reserve, USA, show that marsh retreat has been relatively constant in past decades (McLoughlin et al. 2015, Priestas et al. 2015). This indicates that the system has had enough sediment supply to fulfill what needed for vertical accretion. Other measurements in the Delaware Estuary found that recent rates of marsh retreat are higher than historic ones (Elsey-Quirk et al., 2019b). Similarly, the rate of marsh edge erosion in Barataria Bay, Louisiana, seems to have increased with the rate of sea level (Britsch and Dumbar 1993). Clearly this question is of great relevance considering that marsh survival might stem from the competition between edge retreat and upland migration.

## 6. The biophysical processes governing the marsh-upland boundary

The landward extent of a salt marsh is defined by the boundary between the marsh and adjacent upland ecosystems such as forests, freshwater wetlands, agricultural fields and urban landscapes. As sea-level rises, upland environments become more frequently inundated with salt water. The stress that inundation puts on upland vegetation can convert upland environments into salt marshes, leading to the migration of marshes into uplands in a process of coastal ecosystem transgression. Predicting the spatial distribution of marshes and other coastal land covers requires a clear understanding of the biophysical controls on the rate at which marshes migrate into uplands. Marsh migration also replaces the ecosystem services provided by uplands for those provided by marshes, and it comes with costs and benefits that determine how people respond to ecosystem transgression. Actions taken by stakeholders can slow or facilitate transgression, so a complete model of marsh evolution must account for the biophysical and the social controls on marsh migration.

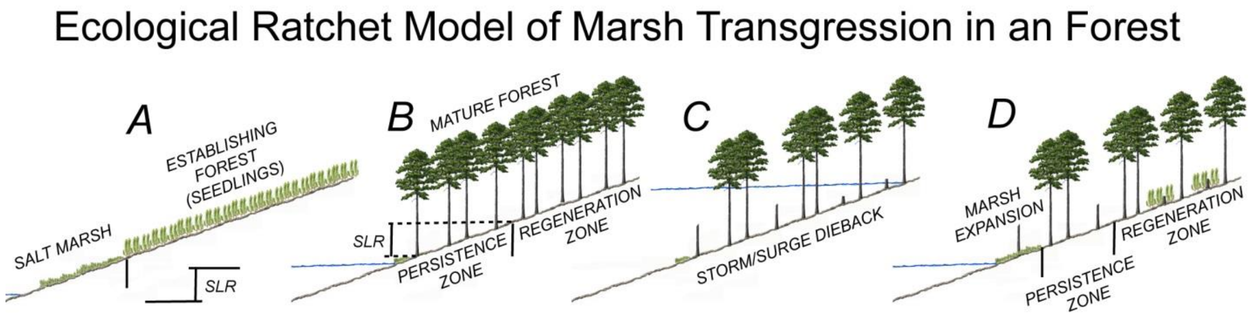


**Figure 4**. Ecological ratchet model of marsh transgression in a coastal forest. After forest establishment (A) sea level rises, creating a persistence zone where mature trees survive under stress but cannot regenerate (B). A storm hits the forest triggering a dieback (C). Only in the regenerative zone seedlings can grow back and the forest recovers, while the marsh expands in the persistence zone. Note that the upper boundary of the persistence zone moves with sea level (press disturbance), while the lower boundary moves during storms (pulse disturbance) (from Fagherazzi et al 2019a).

The regular inundation of the tides defines salt marshes. In contrast, upland environments are dominated by the exchange of water with the atmosphere through precipitation and evapotranspiration (Brinson et al. 1995). While tidal inundation is a regular semidiurnal or diurnal process in most salt marshes, low frequency tidal harmonics as well as meteorological processes lead to temporal variability in the landward limit of salt water inundation. An idealized transect from marsh through upland is therefore situated on a hydrological gradient. The most seaward low marsh sees a twice-daily lateral exchange of salt water. Moving landward and upward, the frequency and duration of tidal inundation decrease until we reach the true upland which is not typically flooded by salt water, though large storm surges can inundate this region. This hydrological gradient can be modified by lateral surface and subsurface inputs of freshwater (Williams et al. 2007).

Inundation with saline water puts stress on the plants that occupy the coastal zone. Oxygen is quickly consumed in flooded soils and reduced compounds, such as sulfides, accumulate and can be toxic to plants (Ponnamperuma 1984; Pezeshki et al. 1990). Stresses experienced by plants grown in saline soils include the toxic accumulation of ions in foliage and water stress due to the higher osmotic potential of salt water (Pezeshki et al. 1990). There are also interactions between flooding and salinity stress that makes the combination of the two more damaging than either stress alone (Pezeshki et al., 1990; Barrett-Lennard 2003). Plants are generally much more vulnerable to both flooding and salinity stress during germination and as seedlings (Kozlowski 1984; Pezeshki et al., 1990) than they are as mature trees.

Only plants which are able to withstand these stresses are able to grow. However, organisms are able to tolerate damage from certain levels of stress (resistance) and to recover from damaging stresses (resilience) (Fernandes et al. 2018). It is therefore not the instantaneous stress that determines a plant's ability to survive but the accumulation of that stress over time, subject to the plant's inherent resistance and resilience. The landward hydrological gradient filters the plant community and forms a zonation that is determined by each plant species' ability to tolerate the temporal pattern of stresses associated with a particular site (Gedan and Fernández-Pascual 2019).

Salt marshes are dominated by halophytic plants such as the *Spartina* grasses. As inundation decreases landward, plants need to be less salt and flooding tolerant. Low marsh becomes high marsh, which gives way to upland plant communities. The exact nature of those upland communities varies widely with setting from pine and hardwood forests in drier areas to forested freshwater wetlands. A wide variety of crops are grown on agricultural uplands, and grass lawns are also an important upland community in suburban landscapes (Anisfeld et al., 2017). It is also common to see a transitional community between the marsh and the true upland communities with salt-tolerant shrubs such as *Iva frutescens*, *Baccharis halimifolia* and *Morella cerifera* as well as the grass *Phragmites australis* (Smith 2013; Kearney et al. 2019).

To understand the response of upland ecosystems to sea level rise is challenging. Compared to salt marshes terrestrial environments have more plant species, each reacting differently to stress. Furthermore, several stressors (soil salinity, flooding, wind, and salt spray) can act in combination to facilitate the replacement of upland ecosystems with salt marshes.

More detailed studies are clearly needed to determine the response of each upland plant to sea level rise, as well as the feedbacks among different species. In order to predict marsh transgression, these ecological studies should provide a common framework based on quantitative expressions that can be readily applied to different species along different shorelines. For example, the ecogeomorphic feedbacks between vegetation and accretion on the marsh surface are all expressed with equations based on biomass and elevation (Morris et al., 2002). This general framework can easily be applied to different species in different marshes. Unfortunately such general expressions quantifying the effect of sea level rise on upland ecosystems are still unavailable, so it is imperative to develop them to build predictive models.

## 7. Presses and pulses affecting the marsh-upland boundary

The inherent temporal variability of water level along the coast means that plants are likely to be exposed to levels of flooding and salinity stress that exceed their inherent physiological tolerances at some point. These disturbances to the hydrological regime can kill plants and change the plant community at a given location. We can classify disturbances into pulses, in which stress levels are high but short-lived and presses, where the stress slowly increases over time.

Storm surges are the key hydrological pulse disturbance that can expose upland plant communities to the damaging impacts of flooding and salinity (Merry et al. 2009; Fernandes et al. 2018). However, it is important to note that other short-lived disturbances do occur in coastal landscapes. Storms cause wind damage, and salt spray can damage the canopy in the absence of inundation (Wells and Shunk 1938; Merry et al. 2009). Droughts are particularly important because a reduction in the supply of freshwater allows saline groundwater to intrude further landward, which can again cause salinity stress in the absence of inundation (Desantis et al. 2007).

A pulse disturbance can have severe impacts on a landscape, causing widespread plant mortality as well as geomorphic change. However, if conditions return to their previous state after the pulse, upland plant communities can likely recover and the total amount of land cover change is likely to be small (Fagherazzi et al. 2019b). However, gradual presses can change landscape conditions and prevent recovery after a pulse disturbance. Sea-level rise applies this press on coastal landscapes, pushing both the limit of tidal inundation and the subsurface freshwater-saltwater interface landward. The replacement of forests by marsh tends to follow a pattern in which regeneration fails before mature trees begin to die, because of the lower stress tolerance of plants during germination and as seedlings (Williams et al. 1999; Kearney et al. 2019). Stress then begins to affect the mature trees, leading to the thinning of the canopy. Marsh grasses have low shade tolerance, so they are generally incapable of migrating under a full canopy (Brinson et al. 1995; Poulter et al. 2008), but they can encroach after canopy thinning.

The effects of pulses and presses can be summarized by an ecological ratchet model for coastal land cover change (Figure 4, Kearney et al. 2019). The hydrological gradient can be schematized with a statistical distribution that describes how likely the water level is to exceed a certain elevation in a given year. This distribution includes both normal tidal variations and storm surges, but it necessarily decreases with elevation and distance from the shore. Each plant community is associated with a specific flooding tolerance threshold, a probability of water level exceedance that they are unable to withstand, or, equivalently, the return time of the flood that would absolutely exceed their tolerance, since the return time is the inverse of the exceedance probability. The exact value of this probability is a complex function of physiological thresholds and local biotic and abiotic factors. For example, outflows of fresh groundwater can maintain forests at lower elevations than they might survive at otherwise (Williams et al. 1999). The threshold may also vary between individuals of a given species. Importantly, young trees will have lower tolerance to flooding than mature trees and thus a lower threshold probability.

The topography of the site and the water level exceedance probability maps the threshold flooding probabilities into the spatial zonation of plant communities. Now, by considering scenarios in which the water level distribution or the thresholds change, one can estimate how the boundaries between plant communities will move (Kearney et al. 2019). A rise in sea level will move the water level exceedance distribution upwards. If the threshold probabilities stay the same, this will move the boundaries for each community upwards and landwards by an amount exactly equal to the amount sea level rose over that time period in the vertical and the increase in sea level divided by the slope in the horizontal direction. Of particular interest is the zone of forest in which mature trees are able to survive while young trees are not. Regeneration stops in this persistent zone (Kearney et al. 2019), and the forest will not recover from other disturbances such as storms, fires or disease that kill mature trees. An increase in storminess would appear within this model as an increase in the variance of the water level distribution, and a prolonged drought might be seen as a decrease in the threshold probability as plants experience persistent water stress and decreased freshwater inputs triggering saltwater intrusion (Kearney et al. 2019). All of these processes -- sea-level rise, changes in storminess and drought -- will cause boundaries to move, but they will move the boundary between each plant community by a different amount.

The main challenge for the correct application of this framework is the determination of the flooding/salinity tolerance threshold for each plant species at the marsh boundary. We still lack detailed information on what process kills trees and its temporal frequency. To determine the combined effect of presses and pulses on the marsh boundary is also inherently difficult. This is because storms act within hours while the consequences of sea level rise can only be seen after decades. Long-term, high-resolution measurements are thus deemed necessary, as those provided for example by the Long Term Ecological Research Network (Knapp et al. 2012). The ability to integrate short and long timescales is therefore the main challenge in the study of the marsh-upland boundary.

## 8. The impact of vegetation on hydrodynamics and sediment transport

Deposition of mineral sediments on the marsh platform is controlled by elevation and vegetation characteristics such as stem diameter, height and density. Plant productivity is also closely linked to marsh elevation, tidal range and sediment supply. Process-based models coupling geomorphology and biology are therefore crucial components for understanding salt marsh evolution (Fagherazzi et al., 2013a; Fleri et al., 2019).

Previous work highlights the strong ecogeomorphic feedbacks in these systems (Temmerman et al., 2005; Fagherazzi et al., 2013a; Nardin and Edmonds, 2014; Kirwan and Megonigal, 2014; Nardin et al., 2016). For example, vegetation influences hydraulics, sediment erosion, deposition, and channel morphology (Gran and Paola, 2001; Nepf, 2012; Manners et al., 2015; Fleri et al., 2019). Marsh platform stabilization induced by vegetation can impact the migration of creek meanders, promotes single channelization, and reduces channel width (Simon and Collison, 2002). Recently, new results have improved our understanding of shear-stress partitioning driven by vegetation friction, and the morphodynamic effects of vegetation on channel geometry (Mariotti, 2018).

During flooding, plant stems and leaves influence hydrodynamics by enhancing turbulence, decreasing water velocity (Nepf, 1999, Figure 5). The accompanied decrease in shear stress promotes deposition of fine sediments. It also decreases sediment transport, especially of the coarser fractions (Larsen et al., 2009). At the same time, because of the increased drag within the vegetation canopy, flow velocity increases at the margin of vegetated patches (Luhar and Nepf, 2012; Yager and Schmeeckle, 2013) possibly leading to scour (Temmerman et al., 2007). At the small scale, shear deposits produced at the limits of the flow and individual plants or patches create coherent flow structures (Nepf et al., 2013). These flow structures affect sediment transport and morphodynamic evolution. Flume studies conducted on individual plants show that the placement of vertical stems into a fine sand bed disturbs the migration and evolution of sand bedforms, promoting scour (Follet and Nepf, 2012; Yager and Schmeeckle, 2013; Ortiz et al., 2013). Given the complexity of the processes at play, modeling feedbacks among flow, vegetation, and sediment remains one of the most complex problems in marsh hydro-morphodynamics (Temmerman et al., 2005; Nardin et al., 2014; Solari et al., 2016).

Although laboratory studies have advanced the mechanistic understanding of local-scale interactions among plants, hydraulics, and sediment transport, it is difficult to apply these results to coastal areas. For example, measurements of detailed flow fields and morphological response within real vegetation canopies are scarce.

Monitoring and collecting data on the hydraulic and sediment transport impact of vegetation in natural environments present numerous challenges. Natural marshes display a typically irregular patchiness, with large variations in vegetation species and ground cover. This ecological variability is seldom captured in conceptual and numerical models of vegetation hydrodynamics.

Marsh models incorporating the effect of vegetated surfaces often rely on laboratory results (e.g. Nepf 1999; Mendez and Losada 2004) where pegs or other simple artificial structures are used to mimic vegetation. Detailed field measurements are deemed necessary to create more realistic representations of hydrodynamics in marsh vegetation.

Furthermore, vegetation is typically schematized as a monostand with fixed geometry (e.g. Zong and Nepf 2010), but in reality plant characteristics vary both within a species and for a mixture of species. More research is needed to i) determine the effect of each vegetation species on flow and sediment transport, ii) determine the combined effect of different species in a marsh assemblage.

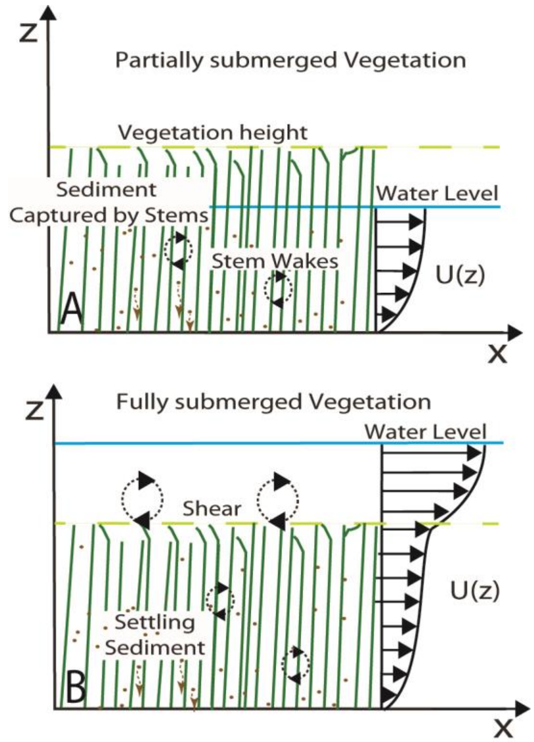


**Figure 5**. Schematization of the hydrodynamics and sediment transport processes acting in vegetated canopies. (A) Vegetation partially submerged and (B) fully submerged (modified from Nardin et al. 2016).

Addressing the spatial variability of vegetation in a numerical model can be computationally expensive. A usual way of modeling the impact of vegetation drag on water flow is applying an augmented friction coefficient (e.g. Manning) in a 2D model. However, this approach neglects important 3D dynamics, such as turbulence and the different effect of submerged and emergent vegetation on flow momentum (Nepf and Ghisalberti 2008; Lapetina and Sheng, 2014). Few high resolution, 3D models have been put forward to account for the impact of vegetative features on hydro-morphodynamics (Baptist et al., 2007; Temmerman et al. 2005; Jin et al. 2007; Horstman et al. 2014; Beudin et al. 2017).

These numerical models are often based on a computational domain with a rectangular or curvilinear grid that might not capture the irregular and patchy distribution of vegetation in natural environments. Unstructured-grid models that allow a spatially variable grid resolution are better suited for this kind of applications, even if they imply an additional numerical computation cost.

## 9. Non-linear dynamics of salt marshes

Wetlands have been widely studied as dynamical systems, i.e., by representing them as points evolving in time within a geometric space (Figure 6). This approach has emphasized a variety of non-linear dynamics, particularly the presence of equilibria and thresholds (also known as tipping points).

The simplest approach is to simulate marshes as a single point representing their spatially averaged bed elevation. One of the main results of this "vertical" approach is the finding of two stable equilibria, one for the vegetated marsh platform and one for the unvegetated mudflat (Fagherazzi et al., 2006; Marani et al., 2010). Negative feedbacks assure the stability of the equilibria: the relationships between vertical accretion and hydroperiod for the marsh platform equilibrium, and the relationship between wave bed shear stress and water depth for the mudflat equilibrium. The marsh platform equilibrium only exists for a certain range of parameters. When the rate of RSLR exceeds a threshold a bifurcation occurs, the stable equilibria disappears, and the marsh drowns. As previously emphasized, a large modeling and field measurement effort has been devoted to quantify this threshold (Marani et al 2010; Kirwan et al. 2010).

In recent years, more attention has been devoted to the "horizontal" dimension, i.e., the lateral extent of the marsh. In this case, a stable equilibrium is not present and the marsh boundary with the mudflat either progrades or retreats (Mariotti and Fagherazzi, 2010; Tambroni and Seminara, 2012, Fagherazzi et al. 2013b). A horizontal equilibrium is present but it is unstable and thus is never achieved in practice. This leads to the marsh edge run-away erosion, which results from the positive feedback between fetch, waves, and marsh edge erosion (Mariotti and Fagherazzi 2013).

Novel insights are obtained by combining the horizontal and vertical dimensions. For example, a three-points model (two points for the mudflat and marsh elevation, one point for the marsh position) revealed feedbacks between the horizontal and vertical component, specifically that marsh lateral erosion favors marsh vertical accretion (Mariotti and Carr, 2014). More cascade-effects were found in a nine-points model that considered a barrier island and two distinct marshes (one adjacent to the mainland and one behind the barrier island) (Lorenzo-Trueba and Mariotti, 2017).

We noticed that feedbacks often arise in models whose dynamics stems from sediment mass-conservation. These feedbacks tend to be negative, e.g., as one compartment of the system is eroding, other compartments receive more sediment. Unfortunately, this feedback also works in the opposite way: as one compartment accretes, other compartments might be sediment starved (e.g., the Bruun-rule interpretation of marsh edge retreat). These feedbacks are also present in other aggregated models for coastal evolution, such as the ASMITA model, which includes a tidal flat, channel, and ebb delta compartment (Townend et al., 2016).

The dynamical system approach is very powerful and should be extended to include novel schematizations of the marsh system. The general pathway to create such models is based on three steps: 1) the use of highly detailed hydrodynamic models to identify feedbacks (e.g. Donatelli et al., 2018; Mariotti et al., 2010), 2) the schematization and aggregation of the system into geometric compartments (i.e., points), 3) the formulation of simplified, yet mass-conserving, fluxes between the compartments.

We suggest that these models should devote particular attention to the sediment concentration that drives marsh vertical accretion. Even without solving the detailed erosion-transport-deposition equations, the sediment concentration should include some sort of mass-conservation feedbacks. In particular, these feedbacks should imply that the available sediment concentration would depend on (and likely decrease with) the rate of RSLR. This modeling component would drastically affect predictions of future marsh response to RSLR, given that nearly all existing models assume a fixed suspended sediment concentration (Kirwan et al., 2016b; Schuerch et al., 2018).

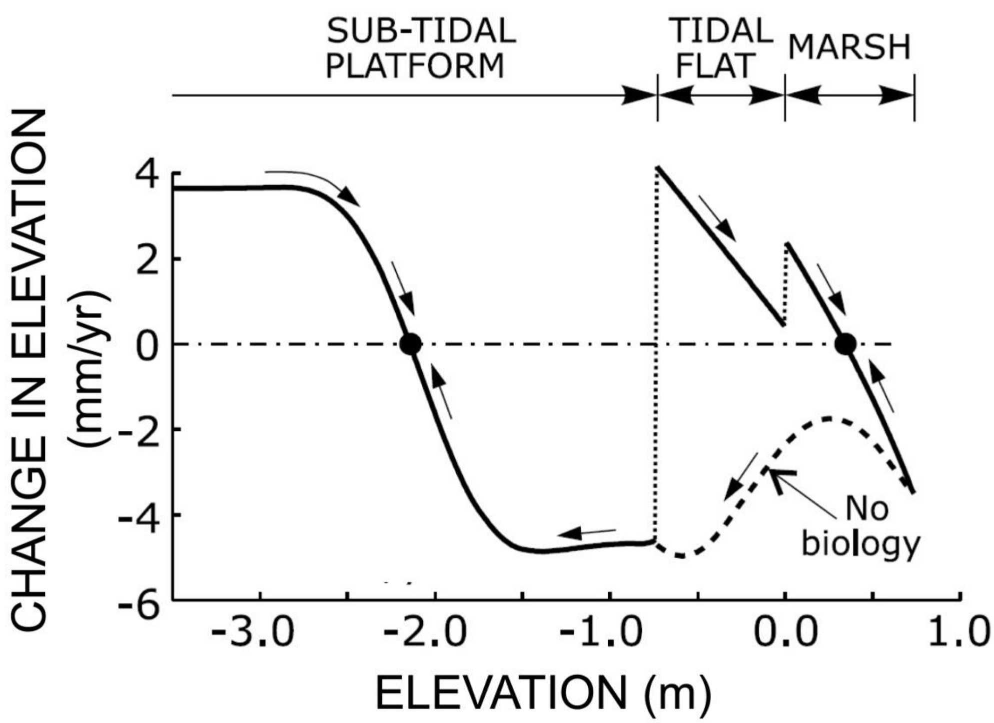

**Figure 6**. Stable states in an intertidal landscape. The right equilibrium point is a tidal flat while the left equilibrium point is a salt marsh dominated by *Spartina alterniflora* (adapted from Marani et al. 2007)

## 10. Assessment of marsh vulnerability and resilience through sediment fluxes

Dynamical models indicate that detailed sediment budgets can help assess the long-term fate of coastal wetlands, because such budgets represent spatially integrated measures of competing constructive and destructive forces. For instance, a sustained sediment deficit can indicate the drowning and/or lateral contraction of a marsh (Fagherazzi et al., 2013b; Ganju et al., 2017).

Even though in some environments marshes can subsist entirely on organic production (Turner et al. 2004), the availability of inorganic sediments is necessary for the maintenance of the marsh geomorphic complex in a period of sea level rise (e.g. Ganju et al., 2017). When accounting for sediment fluxes contribution to wetlands stability, it is necessary to take into account: i) the location of the source of sediments, ii) the location of the wetland respect to the source, iii) mechanisms and timescales for sediment remobilization; and iv) the advection and timescale for the remobilized sediments (Friedrichs and Perry, 2001; Ganju et al. 2013). Sediment sources are diverse and can be both internal and external with respect to the marsh-tidal flat complex. External sources can include sediments from neighboring coasts, from the seafloor, and riverine sediment discharge. Internal sources can include sediments coming from erosion and sediment resuspension of adjacent tidal flats and tidal channels, or sediments eroded from marsh edges. The sediment liberated from eroded marshland may deposit elsewhere on the complex and remain available for resuspension and re-delivery to the marsh platform, or it may be exported from the entire system through hydrodynamic processes (Ganju et al. 2013; Ma et al., 2014; Schuerch et al., 2014; Leonardi et al., 2018).

A stable marsh complex is generally characterized by a consistent input of external sediments which are regularly remobilized. The distance between the sediment source and the salt marsh should then be less than the tidal excursion. The tidal excursion, defined as the product between tidal velocity and single tidal phase (e.g., 6.21 hr) can be considered as a proxy for the transport length and connectivity across the system (Zhang et al. 2019). Therefore, tidal channels within one tidal excursion from the source can benefit from a steady and regular supply of sediments at the tidal timescale.

It has been suggested that sediment flux measurements through tidal wetlands channels can be an integrative metric summarizing the tidally regulated sediment transport (Ganju et al., 2013). For sediments to be efficiently trapped within the marsh complex, they have to be delivered to the marsh platforms and this normally happens during inundation periods. The occurrence of storms can support such delivery through increased mobilization of intertidal sediments due to high waves' bed-shear stress and increased water levels during surge occurrence. Within this context, modelling studies of Schuerch et al. (2013) illustrate the importance of frequently inundating gale events in comparison to extreme scenarios, and suggest that the frequency of inundation is more important than the magnitude because the frequency of extreme water levels is significantly smaller and exponentially decreases with water level. This is supported by field results in the Danish peninsula of Skallingen where a single extreme event could contribute 7.5% to the annual sediment deposition, whereas regularly occurring gale winds can contribute 71% (Bartholdy et al., 2004).

The input of sediment from the ocean represents a fundamental gap in our understanding of marsh dynamics. Numerical simulations carried out by Castagno et al. (2018) indicate that storms import a net volume of sediments in a series of marsh dominated bays in Virginia, USA. A detailed marsh budget in Plum Island Sound, Massachusetts USA, shows that at least 60% of the sediment used for marsh accretion must have a marine or coastal origin (Hopkinson et al. 2018). Contrary to riverine sediment inputs that are well constrained, direct long-term measurements of marine sediment fluxes are scarce. Few monitoring stations along the coast cannot provide the spatial resolution to capture all the sediment fluxes toward and away from marshes. Instrumentation of tidal inlets is also challenging because of the high wave and tidal energy. Finally, sediment concentration in ocean waters can be relatively low and thus difficult to measure. Remote sensing of ocean color could provide the key information to constrain the sediment fluxes between marshes and the ocean (Volpe et al. 2011).

Ganju et al., (2017) have shown that the sediment budget of the marsh-tidal flat complex scales with the unvegetated/vegetated marsh ratio of the estuarine system suggesting that this metric can be used as an indicator of marsh vulnerability. However, external agents are not the only factors influencing the transport patterns and marsh capability to retain sediments, and the eco-geomorphological evolution of the marsh complex can also cause spatial and temporal variability in the sediment budget (e.g. Temmerman et al., 2005; Li and Yang, 2009; Mei et al., 2016; Donatelli et al., 2018; Donatelli et al., 2019; Zhang et al., 2019).

Therefore the grand challenge for the determination of marsh resilience to sea level rise is the quantification of all sediment fluxes in and out of the system, both during fair weather and storms. To this end a multidisciplinary approach can be adopted, combining direct field measurements of sediment discharge with numerical models, variations in topography and bathymetry, and geochemical proxies to determine sediment sources (e.g. Hopkinson et al 2018). Geological investigations can also provide clues on the past extension of marshes and related sediment volumes (Gunnell et al., 2013).

Recent results from Donatelli et al., (2018) have shown that marsh erosion is pivotal for determining the sediment storage capability of whole embayments and that, as salt marsh areas decrease, the amount of sediments trapped within the embayment also decreases. This decrease in sediment trapping includes sediments trapped on tidal flats as well as sediments trapped on marsh platforms. Changes in sediment budgets are related to the fact that salt marsh erosion influences estuarine dynamics through changes in estuarine geometry and removal of vegetated areas. Changes in estuarine geometry can cause: i) creation of new tidal flat area, ii) increase in tidal prism; and iii) changes in local flow patterns. The creation of new tidal flat areas increases the bed shear stress of areas which were previously only inundated during high tide and thus characterized by relatively low average shear stress values. Newly created tidal flat areas represent a new source of sediments which are available for resuspension with respect to pre-erosion conditions. Finally, larger tidal flats can also cause an increase in fetch values and promote the generation of higher waves potentially impacting salt marshes.

An increase in tidal prism, can also cause significant changes in tidal hydrodynamics. For instance, it can increase tidal currents, and tidally-induced sediment resuspension. Furthermore, changes in tidal prism can trigger a change in tidal amplitude and alter the delivery of sediments to marsh platforms (Donatelli et al., 2018; Xiaorong et al., 2018). For instance, results for Barnegat Bay, USA have shown that a decrease in marsh area causes an increase in the estuarine basin and in the tidal prism. As a consequence of the greater tidal prism, the filling time of the bay also increases, as well as the phase lag of the tidal signal. When the phase lag increases, the high water levels are damped and this reduces the time during which salt marshes gets submerged (Donatelli et al., 2018). These results were valid for those areas where an increase in filling time, rather than a decrease in friction, was the main consequence associated to salt marsh erosion. This condition is more likely to happen for those embayments where marshes are located at the boundary with the mainland rather than for a situation where wetlands are scattered at the centre of the embayment (Donatelli et al., 2018, Figure 7). Similar results in relation to the importance of salt marshes for the trapping of sediments have been presented for a macro-tidal system in the UK, where salt marsh erosion has been found to cause an increase in the export of sediments which was related to increasing peaks of suspended sediment concentration (Xiaorong et al., 2018).

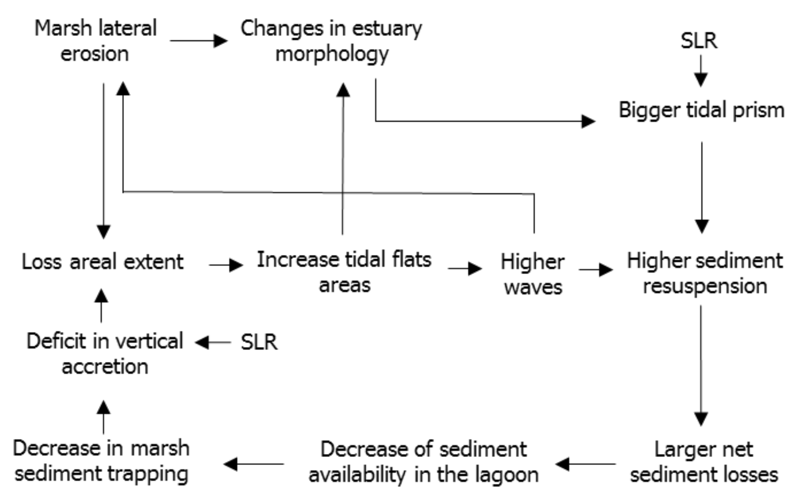


**Figure 7**. a) Positive feedback between marsh erosion and changes in the sediments budget. The decrease in marsh areal extent can trigger a positive feedback loop causing further marsh degradation due to a decrease in the sediments budget (Figure adapted from Donatelli et al., 2018).

## 11. Novel techniques and challenges in high-resolution physically-based numerical models of salt marshes

Simplified zero-dimensional models for the long-term evolution of salt marsh systems are useful tools to identify equilibrium points and compute the approximated "lumped" (i.e. spatially averaged) evolution of each component. However, they present the following drawbacks. First, channel hydrodynamics (momentum and continuity) is not explicitly solved. A zero-order approximation for tidal hydrodynamics is usually employed, consisting of a quasi-static model which considers a horizontal water surface, therefore neglecting the momentum equation and retaining only continuity (Mariotti and Fagherazzi, 2010). This approximation is strictly valid for short tidal channels (sensus Fagherazzi et al., 2003). For longer channels, spatial gradients become important; and tidal range (and, in second order of importance, mean sea level) can significantly vary (Lanzoni and Seminara, 1998; van Der Wegen et al., 2008; Rose and Bashkaran, 2017). As a result, different marsh locations are subjected to different hydroperiods (Rodriguez et al., 2017).

Second, in point models a fixed value of sediment concentration is prescribed at the channel-mudflat boundary, therefore neglecting its spatial and temporal variations. Concentration can decrease along-channel due to variations in tidal velocity, mean tidal range, and bed material (Lanzoni and Seminara, 2002). Concentration can also vary in time due to neap-spring water level variations (modulation of S2 and M2 astronomical components), to the presence of overtides and compound tides (Bonaldo and Di Silvio, 2013) and to wind set-up/set-down (Wiberg et al., 2019).

Third, the geomorphic feedback between mudflats, marshes and tidal channels is highly simplified, since the three components are represented by a single bed elevation, while in reality they all tend to establish equilibrium bed profiles, which are dictated by strong gradients in hydrodynamics, sediment transport, and vegetation.

Fourth, marsh edge erosion depends on wind waves, the characteristics of which are usually determined by using an equilibrium approach (Mariotti and Fagherazzi, 2010) and a spatially constant water level. In reality, waves are controlled by the three-dimensional shape of mudflats and channels, as well as by time- and space-varying water levels. Also, due to the expansion or contraction of marshes, mudflats, and channels, both wave fetch and marsh edge perimeter could vary in a very irregular or even discontinuous way (Mariotti and Canestrelli, 2017).

Models employing simplified equations are able to reproduce two-dimensional tidal networks (Kirwan and Murray 2007, D'Alpaos et al. 2005). However, since they do not solve for tidal propagation in the channels and in intertidal areas, they fail to compute spatial variations of water level and sediment concentration, and their impact on morphodynamics.

Thanks to the steady increase in computational power, we are now able to solve for the spatially-explicit evolution of tidal regions on centuries to millennia timescales by means of the so-called ‘‘simulation models’’ (Murray, 2003), here referred to as "high-resolution" models. With these models, the relevant conservation equations (momentum and mass for the fluid, mass of bed material and suspended load for the sediments) are solved in a semi-coupled fashion. At each iteration, a flow field is computed by solving the hydrodynamic equations (i.e. 2D shallow water equations), and it is used to compute sediment transport and morphological changes. These are passed back to the hydrodynamic module, which computes an updated flow field, and so on. In the past decade, even though these models have been employed to simulate deltas (Edmonds and Slingerland, 2010; Canestrelli et al., 2014a), estuaries (Canestrelli et al, 2014b; Olabarrieta et al., 2018) and inlets (Nienhuis et al., 2016), their use for studying the long-term evolution of the salt marsh-tidal flat-tidal channel complex has been very limited. Marsh processes usually included in simplified models, such as the stabilizing effect of vegetation, organogenic accretion, wind waves and edge erosion, are often neglected in high resolution models (van der Wegen and Roelvink, 2008, 2012; van Maanen et al., 2013; Zhou et al., 2014; Olabarrieta et al., 2018; Donatelli et al., 2018). Although studies that include wind waves in a coupled morphodynamic simulation exist, they are typically run for few decades and do not include a marsh evolution module (e.g. van Ledden et al., 2006; Vested et al., 2013; Hunt et al., 2015).

The first attempt to study the century-scale morphodynamic evolution of a single salt marsh flanked by a tidal channel was proposed by Belliard et al. (2015). The model included space- and time-varying vegetation and organogenic accretion, but neglected wind waves and marsh edge erosion. One of the few models solving for the long-term evolution of salt marshes at basin scale has been recently presented by Mariotti and Canestrelli (2017). By including marsh edge erosion and spatially and temporally varying wind, wind waves, and vegetation encroachment, the model explicitly solves for the planar extension of the marshes.

Figure 8 shows the morphological evolution of a marsh complex using this model. The simulations assume a relative rate of sea level rise of 1 mm/yr and different rates of sediment supply. Only mud is included in the framework.

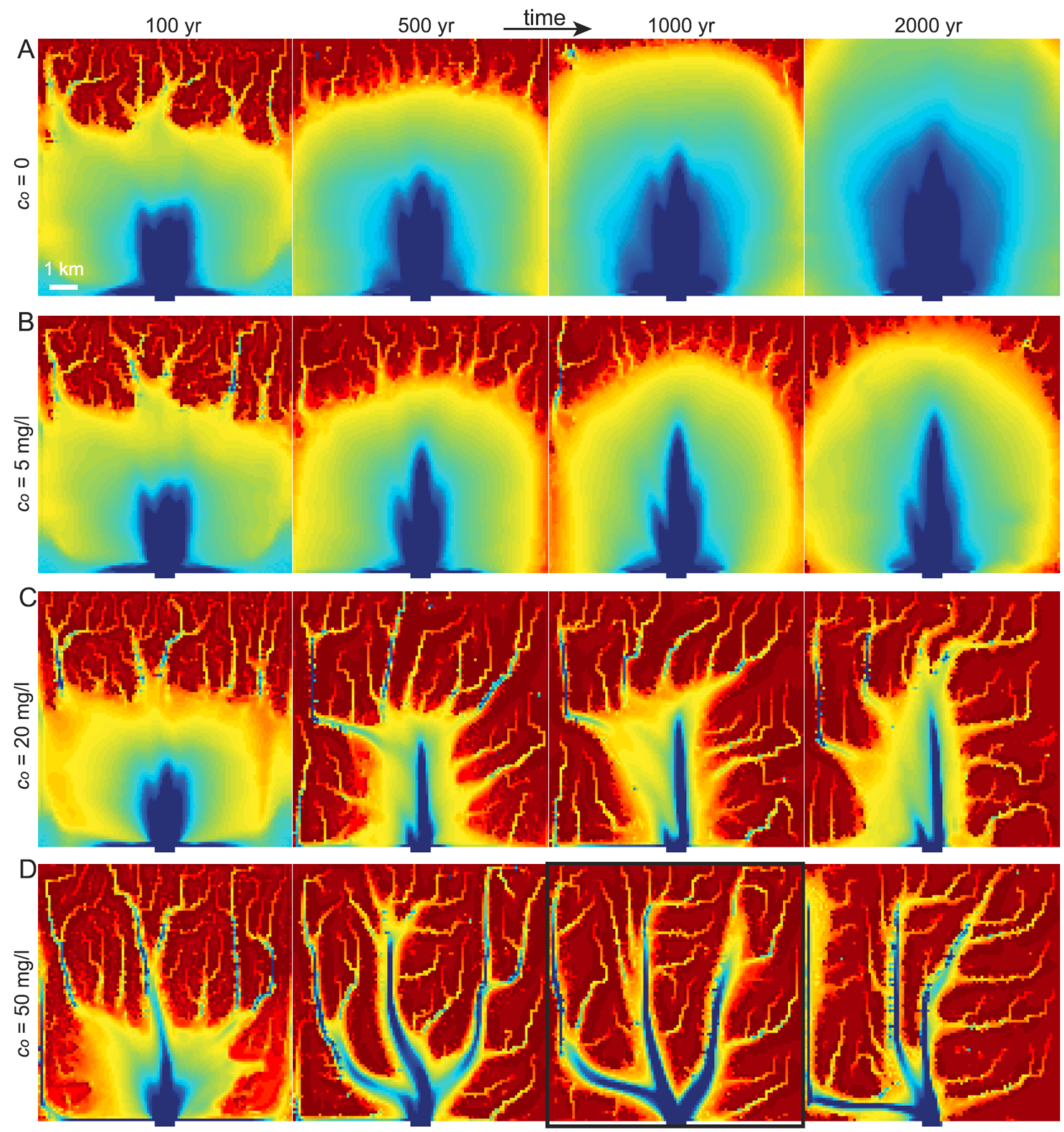


**Figure 8**. Morphological evolution of an initially empty basin with a SLR rate of 1 mm/yr, and for four different sediment concentrations at the inlet (0, 5, 20, and 50 mg/L). Re-adapted from Mariotti and Canestrelli (2017).

Contrary to previous results (Mariotti and Fagherazzi, 2013), these simulations show that tidal currents keep the channels open and prevent the basin from completely filling with marshland even with a large sediment supply. This dynamics was not captured in 0-D marsh models.

Despite the insight provided by physically-based high-resolution models, we here recognize several challenges which we need to face in order to provide more realistic simulations. The first challenge is related to the smallest spatial scale that can be resolved by a space-explicit model. In Mariotti and Canestrelli (2017, Figure 8) only the larger channels (width>100m) were resolved by the model, while the smaller creeks could not be reproduced. These creeks could play an important role in exchanging sediments and nutrients with the adjacent marshes. The resolved scale can be reduced by increasing computational power, but it is still challenging to go below the 10m spatial scale.

Another challenge is related to the offshore boundary conditions. Although Mariotti and Canestrelli (2017) model explicitly accounted for spatial (along-channel) and temporal (e.g. neap-spring) variations in sediment concentration, the problem of prescribing a representative concentration at the boundary has not been completely solved. Models usually prescribe a sediment concentration at the tidal inlet of coastal bays. This simple approach allows ignoring complex continental shelf dynamics, consisting of cross-shore sediment transport by waves, and longshore transport due to currents. Further research is needed to understand to which extent a constant concentration is representative of the average input over a not-yet-well-defined time scale. The same reasoning applies to a time-varying sediment input entering the tidal basin from a freshwater river. How this input affects the long term evolution of the system has also to be investigated.

Another challenge is how to include both cohesive and non-cohesive sediments. Morphodynamic models of coastal regions have historically considered sand rather than mud since the focus was on tidal deltas, tidal inlets and barrier island (van der Wegen and Roelvink, 2008; Dissanayake et al., 2012a, 2012b; van Maanen et al., 2013; Schwarz et al., 2014; Zhou et al., 2014). In reality, most of intertidal deposits, i.e. in mudflats and marshes, are composed of mud, with sand depositing close to inlets and other energetic areas (Frey and Howard, 1986; Oertel et al., 1989). Mud has a much higher mobility than sand, and can be easily delivered to locations farther from the shore. By including also sand, simulations could show whether grain-size distribution affects the morphodynamics of intertidal areas. To this end, the model has to include stratigraphic bookkeeping, and take into account the depositional history of organic, cohesive and non-cohesive layers. As for shallow subsidence, it is usually taken in account by assuming a steady-state bulk density (Kirwan et al. 2016a, Morris et al. 2016) or by lumping its effect into RSLR (Mariotti and Canestrelli, 2017). However, this does not account for spatial variations in soil compaction. Spatially explicit models can solve for spatially varying subsidence, by means of stratigraphic bookkeeping and by including a mechanic module for soil compaction. However, this would further increase the computational cost of the simulations and memory requirements.

Another important process often neglected is the effect of wind set-up/set-down (Wiberg et al., 2019). Wind not only generates wind waves, but also varies the hydroperiod by changing the probability distribution of water levels. Other processes usually not included in the models are bioturbation, the presence of herbivory and the impact of freezing and ice on marsh morphology (Wiberg et al, 2019).

Probably the major challenge that we face is validating high resolution basin scale models with field data. Ideally salt marsh models should be able to hindcast site-specific marsh variations, but the necessary spatially distributed data are not available yet. Remote sensing allows for a relatively easy detection of marsh morphology at basin scale. Note that if morphological changes are known with great precision, boundary conditions (wind, sediment concentration, tides and surges) need to be prescribed with similar precision.

## 12. Novel techniques and challenges in remote sensing of salt marshes

Traditionally, remote-sensing mapping of salt marsh topography and vegetation characteristics is based on either passive multispectral and hyperspectral techniques or active LIght Detection And Ranging (LIDAR) techniques. With hyperspectral techniques, the marsh habitat is mapped employing spectral information, such as the Normalized Difference Vegetation index (NDVI). However, spectral data does not provide the topographic information necessary to fully reconstruct marsh morphodynamic processes (Hladik et al., 2013). On the contrary, thanks to its ability to penetrate through vegetation, LIDAR is more effective at measuring ground elevations. Laser penetration is limited in dense salt marsh vegetation, and it tends to overestimate salt marsh elevations (Hladik et al., 2013). Different approaches have been proposed to reduce this error. Hladik et al. (2013) proposed to include separate corrections for three different height classes of *Spartina alterniflora,* by integrating LIDAR with hyperspectral imagery. These corrections greatly improved the DEM accuracy, reducing the overall mean error. Rogers et al. (2015) investigated light blocking properties of marsh vegetation, and found a species dependent correlation between biomass and vertical obscuration. More recently, Goodwin et al. (2019) produced airborne-LIDAR-derived DEMs for six salt marshes in England with varying tidal ranges and geometries. They also proposed an unsupervised method (Topographic Identification of Platforms, TIP) to differentiate marsh platforms from tidal flats. The method automatically detects scarps and salt marsh platforms from a DEM and does not require manual calibration.

In recent years we witnessed the exponential increase in the number of managers, owners, companies, and scientists employing professional drones equipped with high-resolution visible, multispectral or thermal cameras. Unfortunately, the use of LIDAR in professional drones is less common. This is due to the high cost of both the LIDAR sensor and the drone itself, which has to carry a higher payload (~1-5 kg), and requires an expensive RTK GPS system in order to achieve centimeter accuracy. The recent release of more lightweight laser scanners is making UAV-borne laser scanning (LIDAR) slightly more affordable. UAV-borne LIDAR has been recently used for individual tree detection (Wallace et al., 2014), the 3D mapping of forest canopy structural properties (Wallace et al., 2016), and for the 3D reconstruction of individual mangroves (Yin and Wang, 2019). Wang at al. (2017) employed a UAV-borne LIDAR for obtaining both the canopy height and fractional cover in the Hulunber grassland ecosystem in China. They found a high correlation between mean grass height and fractional cover, while the mean canopy height was in mediocre agreement with aboveground biomass. We are not aware of any contribution investigating the ability of UAV-borne LIDAR to obtain vegetation characteristics in coastal salt marshes. A first attempt to inferring vegetation characteristic from UAV-borne LIDAR is currently undergoing. A LIDAR point cloud was collected using a Velodyne VLP-16 LIDAR sensor mounted on a DJI Matrice 600 UAV. The study area consists of a couple of narrow creeks (width <1m) and their surrounded marshes in Sapelo Island, Georgia, USA (Figure 9). The vegetation almost exclusively consists of *Spartina alterniflora*.

The data was collected in February 2019, during low spring tide, to minimize the presence of water inside the channels, so that bottom elevations were also measured.

The advantages of using an UAV-borne LIDAR with respect to an airborne LIDAR for surveying salt marshes and their channel network are numerous. First, it allows resolving the geometry of smaller creeks (width< 2m, Figure 9). Second, it allows resolving variations in vegetation height that could occur at the spatial scale of tens of cm, as for example at the edges of tidal creeks (Figure 9). Third, it allows resolving small scale topographic variations, notably the high gradients in bed elevation next to tidal creeks, both in the presence and in the absence of levees (Mariotti et al., 2016). Finally, the cost to fly a LIDAR drone is much less than the cost required for a manned flight, at least for small areas.

The choice between UAV or airborne LIDAR strongly depends on the extension of the area of interest, the spatial scale one wants to resolve, and the time available for carrying out the survey.

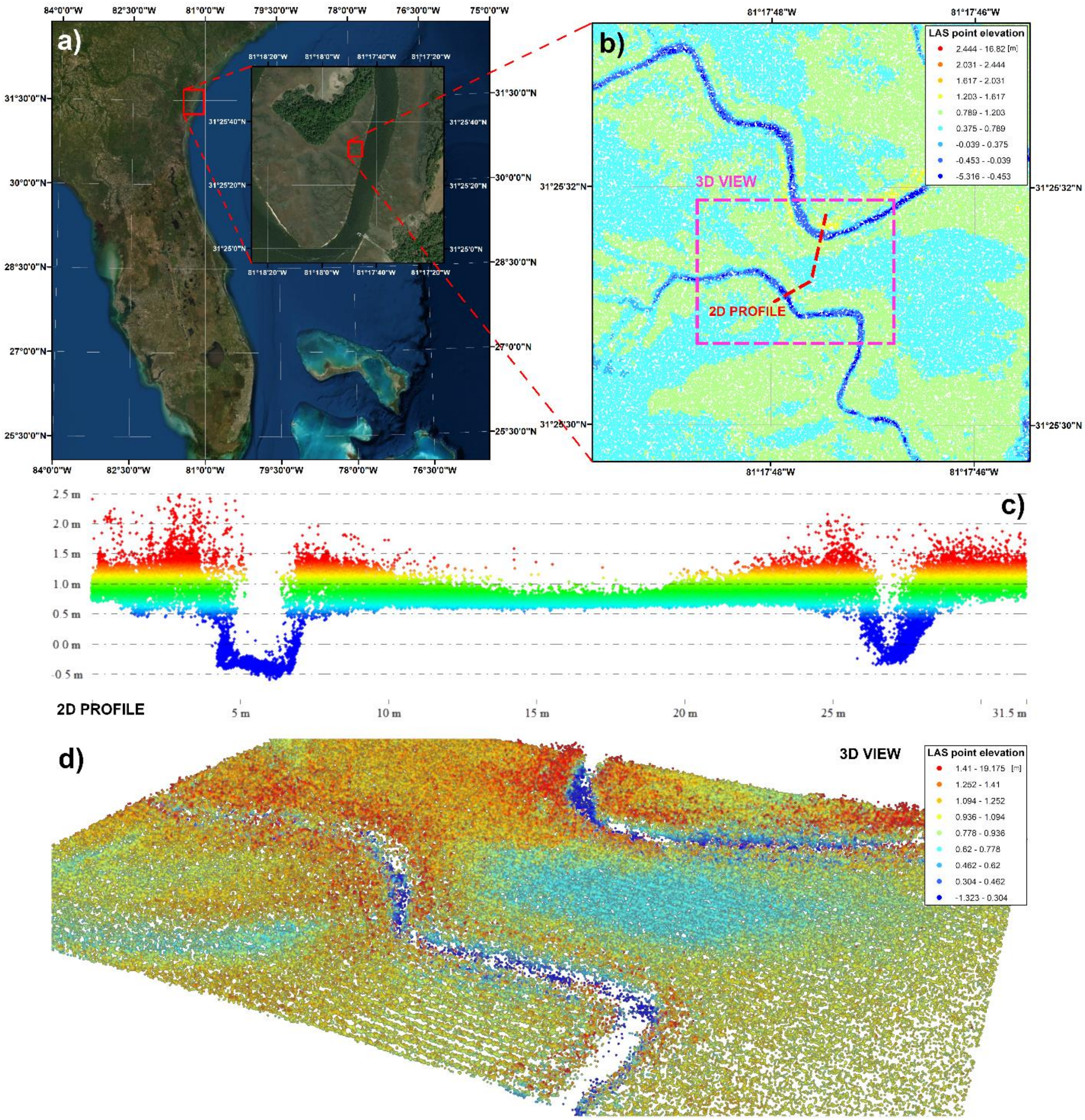


**Figure 9**. a) Study site in Georgia USA. b) Top view of the point cloud determined by the UAV-borne LIDAR. c) Cross sectional view following the red line in (b). d) Three dimensional view of the point cloud.

Satellite multispectral imageries are one of the main sources of remote sensing data for detection of salt marsh vegetation. However, the restricted amount of spectral bands (less than ten) and the recurrent manifestation of mixed pixel (also for medium-high resolution geometric satellites, in the range of 1÷5 m/pixel), restrict the opportunity of high resolution wetland mapping (Hossain et al. 2015; Wicaksono et al. 2017).

Recent developments in Unmanned Aerial Vehicles (UAVs) technology with miniaturization of sensors have facilitated the retrieval of remote sensing images of wetlands. Structure from motion (SfM) can use these images to build accurate terrain models, contours, textured 3D models, and 3D mapping (Nex and Remondino 2014). Multispectral imagers at high resolution (order of cm) derived from UAV allow wetlands monitoring (Taddia et al., 2019). In particular, applications along the coastline might help to identify different ecological zones (Papakonstantinou et al. 2016), determine coastal vegetation features (Duffy et al. 2018), and improve 2D/3D coastal environment characterization (Mancini et al. 2013; Taddia et al. 2019). An application of UAVs at a restored salt marsh in Poplar Island, Maryland, USA, showcases the potential of this new technology (Figure 10). This location presents optimal conditions for UAV-based remote sensing applications, because the marsh is not entirely flooded and the area is small.

A common approach for managing multispectral datasets consists in using structure from motion techniques (SfM) to generate a comprehensive orthomosaic for each band.

The SfM process is an advanced method able to exploit a set of images (Mancini et al. 2013; Hugenholtz et al., 2013; Casella et al., 2016). It enables a 3D geometry reconstruction from a set of 2D images of the scene. The use of UAVs acquired images is particularly beneficial when combined with SfM techniques and provides great results in terms of spatial resolution at a low cost (Westoby et al., 2012; Cook 2017).

Data collected with this technique well capture differences in elevation within a restored marsh (Fig. 10) thus separating the marsh from the surrounding mudflats. It also capture vegetation cover through the Normalized Difference Vegetation Index (NDVI), detecting marsh grasses and biofilms present on mudflats. High resolution datasets like the one presented here can capture salt marsh evolution through repeated mapping of vegetation and marsh topography. These data will inform numerical models and shed light on the impact of sea level rise and storms on salt marshes.

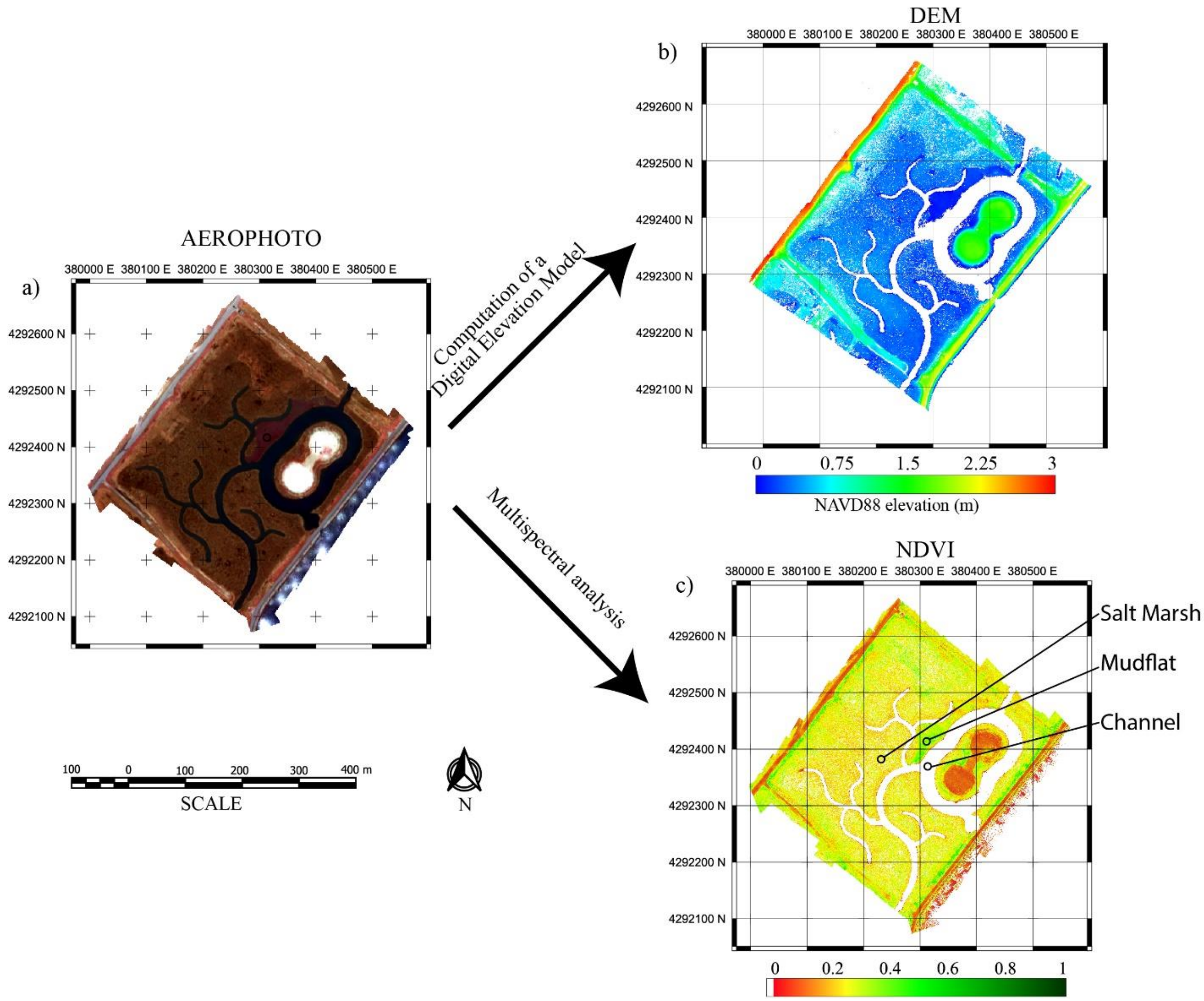


**Figure 10**. a) Orthophoto of a restored marsh in Poplar Island, Maryland b) Digital Terrain Model (DTM) generated as DEM from the ground-classified dense point cloud with Structure form Motion (SfM), c) NDVI map detected on April 2019. High NDVI values on the mudflat highlights the occurrence of biofilm often present in late spring.

Optical remote sensing can also be used to determine the spatial variability of suspended sediment in coastal waters (Volpe et al., 2011). High temporal resolution in remote sensing images can capture the effect of wind waves, river discharge, and tidal fluxes on total suspended sediment (Volpe et al. 2011). Generalized algorithms for the retrieval of suspended sediment concentrations based on hyperspectral data are currently developed using field data from different wetlands in the United States (Jensen et al. 2019). These novel techniques will enable us to map total suspended sediments at very large spatial scales, providing critical boundary conditions for models of salt marsh evolution.

Advances in radar remote sensing are also shedding new light on intertidal hydrodynamics. AirSWOT can measure with high precision water slopes in tidal channels (Altenau et al., 2017), while UAVSAR can quantify variations in water level in flooded vegetated surfaces (Shaw et al., 2016). Together these new techniques will determine how tides and storm surges propagate in intertidal environments. A better understanding of marsh hydrodynamics will constrain hydroperiod, fluxes of sediments, and indirectly the variability in sediment deposition on the marsh platform. Long-term remote sensing data can also quantify the effect of climate forcing on vegetation, sediment availability, and marsh morphology.

## Implications for management and restoration of salt marshes

Salt marshes require sediments in order to accrete and counteract sea level rise. If sediment is abundant, marshes can also expand laterally via progradation (Mariotti and Fagherazzi 2010). Therefore determination of sediment availability for each salt marsh site is critical for both conservation and restoration. A sediments budget represents therefore an important tool to assess the fate of salt marshes in a period of accelerated sea level rise (Fagherazzi et al. 2013b; Hopkinson et al. 2018). A negative sediment budget with a net export of sediment from a salt marsh complex indicates marsh deterioration, while a net sediment input matching or surpassing the accommodation space created by sea level rise indicates marsh survival (Ganju et al. 2017).

Detailed sediment budgets can be used by coastal managers to assess the vulnerability of salt marshes (Ganju 2019). Proxies for sediment fluxes, as for instance the ratio between vegetated and unvegetated area (Ganju et al., 2017), can be easily applied to map marsh vulnerability in the absence of costly field measurements. Sediment budgets can also be used by managers to select coastal locations where marsh restoration is more likely to be successful. High sediment availability seems in fact required to create and maintain new marshes.

Damming of many large rivers has increased the vulnerability of salt marshes, cutting off critical sediment supply for accretion (Syvitski et al., 2005). Salt marshes are therefore finding themselves in a delicate condition, facing accelerated sea level rise exactly when their sources of sediment are reduced (Weston 2104). Application of the sediment budget concept in marsh management would thus suggest the removal of all barriers that limit sediment fluxes to marshes, including dams and levees. This approach has been advocated to mitigate marsh loss in the Mississippi delta, USA. The idea is to allow the sediment load of the Mississippi river to reach the delta marshes by opening control structures in artificial levees, thus diverting part of the river discharge and its sediments to the marshland (Allison and Meselhe 2010).

Recent research results also provide clear advice on whether to prevent lateral marsh erosion. The sediment eroded from marsh boundaries is often necessary for the survival of many marshes. A detailed sediment budget in Plum Island Sound, MA, USA indicate that up to 30% of the sediment needed for marsh accretion is provided by the lateral erosion of marsh edges (Hopkinson et al. 2018). Reinforcement of marsh boundaries with hard structures (e.g. sea walls) could therefore jeopardize the entire marsh system, cutting off this important sediment supply. This example shows how marsh morphodynamics is regulated by complex feedbacks, so that changes in one compartment could reverberate destabilizing the entire system (e.g. Mariotti and

Carr 2014). Only a holistic approach considering all the sediment sources and fluxes of the system should inform marsh restoration and protection projects (Fagherazzi et al. 2013b). Novel results also highlight the importance of hydrological processes in preserving the carbon stock stored in salt marshes. For example, the introduction of salt water in freshwater marshes could lead to organic matter oxidation and subsidence (Stagg et al. 2017). Coastal managers need to consider in detail hydrological changes in the marsh soil and their consequences for marsh stability.

The migration of marshes into uplands changes the ecosystem services that humans obtain from coastal landscapes (Feagin et al. 2010; Schmidt et al. 2014). Tidal wetlands store significantly more carbon per unit area than terrestrial ecosystems (Mcleod et al. 2011), so the conversion of an acre of forest into an acre of marsh increases the total carbon sequestration of a landscape. Likewise, wetlands are sinks for nutrients such as nitrogen (Valiela and Cole 2002; Sousa et al. 2008; Drake et al. 2009) while agricultural uplands are large sources of nutrients, and conversion of uplands to wetlands should therefore remove nutrients from coastal waters. However, the salinization of agricultural land has been shown to release large amounts of legacy nutrients that have accumulated in the soils (Ardón et al. 2013), which could result in short-term coastal eutrophication.

A particular challenge for managing the trangression of coastal ecosystems is the distinction between private and public values of land covers (Schmidt et al. 2014). Uplands like agricultural land and lawns have value to private landowners and urban infrastructure provides clearly defined public value. On the other hand, the ecosystem services provided by salt marshes, such as carbon and nutrient sequestration, have little private value and public value that can be challenging to quantify. When valuable uplands are threatened by coastal transgression, both private landowners and communities may prefer to defend uplands by constructing defenses such as levees or ditches. Removal of already-constructed barriers can allow marshes to migrate, but the public values of expanding marshes must be made clear for these strategies to be considered (Feagin et al. 2010; Schmidt et al. 2014). An alternative to direct conversion of upland to marsh is a facilitated transition where actions such as planting salt-tolerant crops can ease the economic impacts of transgression (Voutsina et al. 2015).

## Grand challenges and directions for future research

Sea level rise and a reduction in sediment supply from rivers are threatening the survival of salt marshes. Models are needed to forecast the fate of these delicate and important ecosystems in the next decades. In recent years our understanding of marsh dynamics has improved, as well as our ability to quantify processes that drive the evolution of the marsh landscape. However, we are still far from having established predictive models for marsh evolution. Here we list the main challenges that, in our viewpoint, need to be addressed:

*Quantify sediment supply to marshes and its future variations*

Sediment supply to marshes and its spatial and temporal variability is often ignored in marsh studies. Yet sediment availability is the key factor controlling accretion and ultimately marsh survival. We need to develop an equivalent sediment concentration that accounts for the temporal variability of sediment supply, including for example storms. Similarly, we need to develop rules to account for the spatial variability of sediment inputs.

*Inclusion of lateral erosion and pond expansion in vertical models of marsh evolution.*

Nowadays we use separate frameworks to address different processes acting on the marsh landscape. Lateral erosion, pond expansion, and vertical accretion must be integrated in the same framework via sediment fluxes. The direct application of point models to simulate large salt marsh swaths should be avoided. Large-scale coarse-resolution models that mostly use a vertical approach might still be used for predictions if ponding and edge erosion are correctly parameterize.

*Salt marshes as a component of an evolving coastal landscape*

Most of the research carried out in recent years focuses solely on marshes, considered as independent landforms. In reality salt marshes are an integral component of a dynamic coastal landscape, always interacting with tidal flats, shorelines, barrier islands, inlets and the upland. Feedbacks between salt marshes and other coastal landforms can strongly affect the geomorphic trajectory of the entire system in a period of accelerated sea level rise. Salt marshes should be connected to other coastal landforms via sediment fluxes, to determine how changes in one landform reverberate across the entire system.

*Variability of marsh vegetation and its effect on hydrodynamics and sediment transport*

Vegetation plays a major role in salt mash resilience. The effect of vegetation on hydrodynamics and sediment transport is quantified with expressions based on simple geometric descriptions of marsh vegetation. However, the number of plant species present in salt marshes is outstanding across continents. Different plant species also interact via facilitation and competition creating well defines vegetation zones. These zones respond to marsh evolution, tracking retreat, expansion, and variations in elevation. Failing to distinguish between different vegetation species from a physical viewpoint would prevent us from capturing the role of different vegetation zones on marsh evolution. The variability of plant forms need to be addressed if we want to correctly capture the feedbacks between vegetation and physical processes.

*Ecological dynamics of the marsh-upland boundary*

The mechanisms that control the horizontal and vertical location of the marsh-upland boundary and the plant community composition across the boundary on decadal time scales are not fully understood. These dynamics will vary dramatically from site-to-site because of different soil characteristics, hydrological conditions, and disturbance regimes. The ratchet model provides one conceptual framework to think about how changes in sea level and disturbance regimes, including storms, will move the marsh-upland boundary. However, it relies on thresholds for plant survival and regeneration that are complex functions of site-specific physical, physiological and ecological characteristics and that are therefore hard to estimate a priori. Synthesis of data on physical forcing and plant community composition from marsh-upland boundaries around the world will be necessary to construct generalizable mechanistic models that can predict marsh-upland boundary evolution.

*Human-environment interactions at the upland boundary*

Human-environment interactions along the marsh-upland boundary are critical determinants of the rate of marsh-upland boundary migration, but human responses to marsh migration are poorly understood. A complete model of coastal landscape evolution must also take into account the values that humans derive from different land covers, the actions that they might take to preserve some of those values at the expense of others and the time value of these decisions. There is also opportunity in using such coupled human-natural models to design and test management strategies that incentivize the removal of barriers to marsh migration and nature-based engineering techniques that facilitate a smooth ecological and economic transition from upland to marsh.

*Integration of remote sensing data in evolution models of salt marshes.*

Spatially distributed data on salt marsh vegetation, hydrodynamics, and morphological change are rare. Yet we need these data to fully understand this complex landscape and to calibrate and test conceptual and numerical models of marsh evolution. Recent developments in remote sensing are generating new datasets with high spatial resolution. Optical sensors are providing us with accurate maps of vegetation and its variations in time. Sediment concentration in channels and nearby waters can also be measured through remote sensing.  LIDAR can measure salt marsh topography at high resolution, while novel radar products can quantify important hydrodynamics parameters like water slope and variations in water level. Availability of low-cost drones will allow us to increase the spatial and temporal resolution of remote sensing datasets. These data will enable researchers to test current hypotheses on salt marsh dynamics, and quantify key processes that were so far only addressed with empirical formulations. In the future we need to integrate these new datasets in our conceptual and numerical models of marsh evolution.

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