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Key Points:
- The paleo-record shows lower thresholds for submergence of marshes and mangroves than the instrumental record
- Accelerated relative sea-level rise will nearly always lead to a reduction in the extent of coastal wetlands
- Integration of new field and remote sensing data with constraints from the paleo-record will enable advances in coastal wetland modeling

Supporting Information:
- Original Version of Manuscript
- Peer Review History
- First Revision of Manuscript
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- Authors' Response to Peer Review Comments

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Coastal Wetland Resilience, Accelerated Sea-Level Rise, and the Importance of Timescale

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Abstract Recent studies have produced conflicting results as to whether coastal wetlands can keep up with present-day and future sea-level rise. The stratigraphic record shows that threshold rates for coastal wetland submergence or retreat are lower than what instrumental records suggest, with wetland extent that shrinks considerably under high rates of sea-level rise. These apparent conflicts can be reconciled by recognizing that many coastal wetlands still possess sufficient elevation capital to cope with sea-level rise, and that processes like sediment compaction, ponding, and wave erosion require multidecadal or longer timescales to drive wetland loss that is in many cases inevitable.

Plain Language Summary The rapid, climate-driven acceleration of global sea level threatens salt marshes and mangroves along low-elevation shorelines. These coastal wetlands provide protection from storms along with other ecosystem services to vulnerable coastal communities, including several megacities. The question of how coastal wetlands will cope with future sea-level rise is a subject of much debate, with recent research providing contradictory answers. Our analysis suggests that much of this can be attributed to the time window under consideration. Even coastal wetlands that are able to persist during the next few decades are likely to be much less resilient through the remainder of this century and beyond.

1. Introduction

Coastal wetlands (marshes and mangroves) are among the most valuable ecosystems on the planet (Barbier, 2019; Costanza et al., 2014), yet they are threatened by accelerated sea-level rise and other human impacts. Coastal wetlands occupy extensive portions of low-elevation coastal zones (LECZs; commonly defined as <10 m above mean sea level) that are home to all or portions of 21 of the 33 largest megacities (population >10 million) worldwide (https://digitallibrary.un.org/record/3799524). Recent work has shown that LECZs are considerably lower in elevation than previously assumed (Kulp & Strauss, 2019) and several LECZs may subside more rapidly than commonly thought (Keogh & Törnqvist, 2019). Given that the acceleration of global sea-level rise will continue well into the future (Oppenheimer et al., 2019), predicting the extent and health of coastal wetlands is a topic of great import.

A recent global-scale prediction of coastal wetland extent for the remainder of this century (Schuerch et al., 2018) has suggested that even under pessimistic climate scenarios, and provided that there is room for landward migration, coastal wetland area will generally increase, echoing previous model studies that have suggested that coastal marshes can keep up with rates of sea-level rise as high as 10–50 mm yr^{-1} (Kirwan et al., 2016). These results stand in stark contrast with studies based on the geologic record that show tipping points for marsh drowning in the Mississippi Delta (USA) at rates of relative sea-level rise (RSLR) of ~3 mm yr^{-1} (Törnqvist et al., 2020) and an inability of mangroves worldwide to initiate sustained accretion when rates of RSLR exceed ~6 mm yr^{-1} (Saintilan et al., 2020). The main purpose of this Commentary is to examine these seemingly contradictory outcomes. We first discuss the concept of accommodation that plays an increasingly important role in models that seek to predict coastal wetland change until the end of this century (e.g., Schuerch et al., 2018). We then make the case that these models must be constrained by the stratigraphic record (i.e., observations over centennial to millennial timescales) and we discuss key reasons why instrumental observations (i.e., annual to decadal timescales) cannot fully capture the outcome

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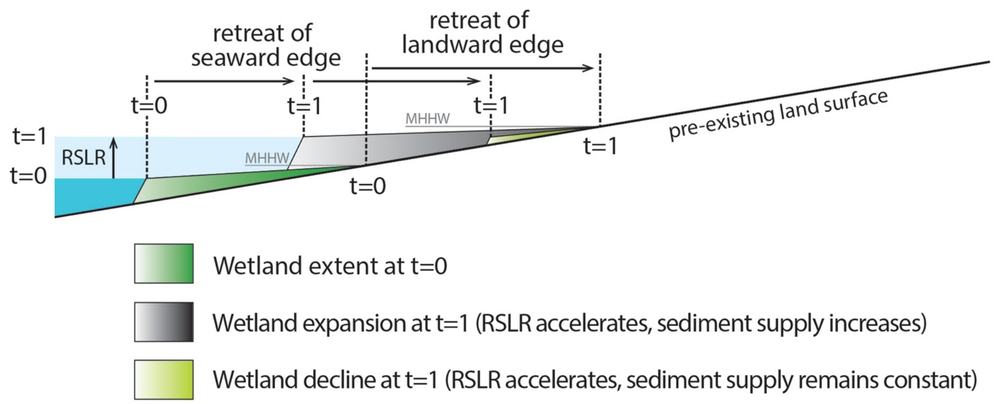

Figure 1. Schematic dip-oriented cross section illustrating coastal wetland evolution on a gently sloping substrate. Relative sea-level rise (RSLR) generates accommodation that may or may not be filled, depending on sediment supply (i.e., depending on the accommodation/supply ratio). Note that the initial condition ($t = 0$) shows a coastal prism that has evolved under modest rates of RSLR, followed by a rapid acceleration of RSLR between $t = 0$ and $t = 1$. The conceptual model illustrates two possible conditions at $t = 1$, both characterized by landward wetland retreat. Wetland expansion (i.e., retreat of the seaward edge that is slower than retreat of the landward edge) is only possible with a major increase in sediment supply to offset the accelerated rate of accommodation creation. A more realistic outcome is a major reduction of wetland area, akin to the conditions illustrated in Figure 3b. Note that in both cases elevation is maintained within the tidal frame, which is critical for long-term sustainability. MHHW, mean higher high water.

of processes that determine the fate of coastal wetlands. We close with a few thoughts on the path forward in this vital area of research.

2. Stratigraphic Coastal Wetland Models and the Role of Accommodation

Coastal wetlands are typically underlain by wedge-shaped sediment bodies (sometimes referred to as "coastal prisms") reflecting the delicate interplay between the topography of the pre-existing landscape, the rate of RSLR, sediment supply, and a host of other physical and biological controls, such as tidal regime, primary productivity, and biogeography (e.g., Allen, 2000; FitzGerald et al., 2008; Woodroffe et al., 2016). It has long been recognized that the persistence of coastal wetlands depends on their ability to migrate both upward and landward with rising sea level. As a result, models of coastal wetland evolution increasingly involve the concept of accommodation—the space that is created due to sea-level rise and land subsidence (i.e., RSLR) and that is available for filling with sediment, both mineral and organic. Stratigraphic models that consider the interplay between RSLR and sediment supply (see e.g., the review by Paola, 2000) can predict coastal wetland evolution over timescales longer than what is typically captured by morphodynamic models.

There is a rich literature in sedimentary geology on the accommodation concept, tracing back to Jervey (1988). The core principle of this and the following studies is that accommodation is fundamentally generated by RSLR. Subsequent work has established the relationship between accommodation and sediment supply (commonly referred to as the A/S ratio) as a primary control on whether a shoreline (along with its associated wetlands) migrates landward, seaward, or remains stationary (Helland-Hansen & Martinsen, 1996; Muto & Steel, 1997; Schlager, 1993) with respect to a pre-existing, gently sloping surface. The hallmark of this stratigraphic theory is that if the rate of creation of accommodation increases, the shoreline must migrate landward. Survival in-place is only possible if there is an increase in sediment supply and/or biogenic accretion. Such an increase must typically be very substantial: an increased lateral extent of a coastal plain requires more sediment to keep up with the rate of accommodation creation (Figure 1). It is important to stress that the A/S theory is scale-independent (i.e., it can be used to examine thick stratigraphic successions representing millions of years as well as present-day coastal environments) and it applies to river deltas as well as to other coastal depositional settings (Muto & Steel, 1997). The robustness of this theory is shown by the fact that it has stood up to scrutiny by means of both experimental data (e.g., Kim et al., 2006) and the stratigraphic record (e.g., Amorosi et al., 2017). The role of accommodation is increasingly ingrained in the coastal wetland literature (e.g., Rogers, 2021; Woodroffe et al., 2016).

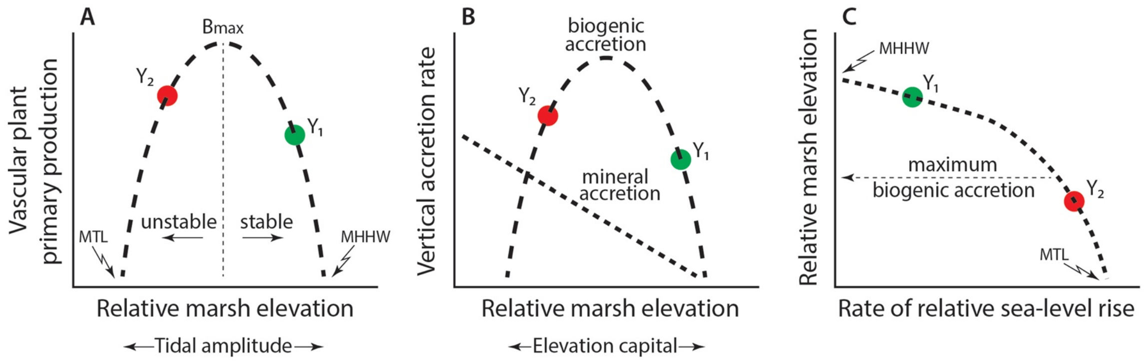

Figure 2. Fundamentals of marsh equilibrium theory (adapted from Morris et al., 2020). Marsh vegetation spans a vertical range equal to about one tidal amplitude occupying the upper half of the tidal frame (a), which also represents the potential elevation capital (b). Biogenic vertical accretion declines to zero at the extremes due to stress from hypoxia at the low end and osmotic stress at the high end. A rising RSLR moves the points along the production and accretion curves to the left. Elevations greater than the optimum (B_{max} in a) are stable (e.g., Y_1). At super-optimal elevations like Y_1, both biogenic and mineral accretion increase with RSLR. Sub-optimal elevations (e.g., Y_2) are unstable in the sense that biogenic accretion decreases with RSLR. Biogenic accretion is more important than mineral accretion at high relative elevations. The equilibrium elevation depends on the rate of RSLR, as shown by the dashed line in (c) with points Y_1 and Y_2. MTL, mean tide level; MHHW, mean higher high water.

Refinement of the A/S theory has shown that shorelines cannot remain stationary under conditions of constant accommodation creation and constant sediment supply. This is due to autoretreat, a geometrically dictated and inevitable result of the fact that a constant sediment volume must be dispersed across a progressively larger coastal plain (as well as a growing foreset in the case of deltas) (Muto & Steel, 1992, 1997; Straub et al., 2015). In conclusion, widely accepted stratigraphic principles show that an increase in the rate of RSLR nearly always leads to landward retreat of the shoreline. Therefore, expansion of coastal wetlands can only occur due to retreat of their landward edge at a rate faster than the retreat of the shoreline. Conversely, an acceleration of RSLR without a change in sediment supply will inevitably lead to a smaller coastal prism that supports narrow, fringing wetlands (Figure 1).

The argument could be made that deficiencies in mineral sediment input could be offset by organic matter produced by wetland vegetation contributing to vertical accretion. While this organic contribution can make a difference when relative elevation is optimal for plant growth (Figure 2), even then there is a limit to primary production and, hence, biogenic accretion (Morris et al., 2016). Furthermore, recent work has shown that even in organic-rich marshes, mud is a key constituent driving vertical accretion (Mariotti et al., 2020).

Next, we highlight the importance of the paleo-record because it offers constraints for stratigraphic models that are not available from the instrumental record.

3. The Importance of Timescale

Studies of the coastal stratigraphic record formed by marsh and mangrove deposits have a long history and play a large role in reconstructions of postglacial sea-level rise. For example, sea-level indicators from these settings account for the vast majority of currently existing Holocene sea-level data (Khan et al., 2019). Once high-resolution sea-level reconstructions are available, these paleo-wetland records offer unique opportunities to study coastal wetland evolution over timescales much longer than the instrumental record, yet it is only recently that such studies have been undertaken. Horton et al. (2018) showed that marshes are 9 times more likely to retreat than expand at rates of RSLR ≥7.1 mm yr^{-1}, based on an analysis of some 50 Holocene records from Great Britain. Threshold rates like these are spatially nonuniform, as indicated by a study from the Mississippi Delta that shows that marsh drowning becomes inevitable once rates of RSLR exceed 3 mm yr^{-1} (Törnqvist et al., 2020). A multitude of factors is likely at play to explain this difference, but a chief contrast between these two regions is the tidal range: dominantly mesotidal or macrotidal in Great Britain versus microtidal in Louisiana (USA). It has long been known (e.g., Reed, 1995) that tidal range is a key determinant of marsh vulnerability. Recent work on mangroves (Saintilan et al., 2020) has found that these ecosystems lose their ability for sustained accretion when RSLR exceeds 6.1 mm yr^{-1}, a threshold that they predict to be surpassed in about 30 years under a pessimistic (RCP8.5) sea-level scenario.

Even though specific numbers vary, it appears that paleo-records consistently produce lower threshold rates for coastal wetland submergence than what has been inferred from instrumental records. This is illustrated by studies from Louisiana where Jankowski et al. (2017) showed that many marshes can still keep up with present-day rates of RSLR, despite the 3 mm yr^{-1} tipping point for marsh drowning found for the Mississippi Delta by Törnqvist et al. (2020), a rate that has already been exceeded by present-day global sea-level rise (WCRP Global Sea Level Budget Group, 2018). In a similar fashion, paleo-records of mangrove evolution (Saintilan et al., 2020) have led to pessimistic predictions for mangrove survival (submergence in about 30 years), while instrumental records suggest that the majority of mangroves will persist through the end of this century under the RCP8.5 scenario (Lovelock et al., 2015).

How can this apparent conflict be explained? We suggest that these observations can be reconciled by taking account of the fact that coastal wetland submergence and retreat take time. As shown for the Mississippi Delta, marsh drowning takes about 50 years when the rate of RSLR exceeds 6–9 mm yr^{-1}, that is, longer than most instrumental records. Marsh and mangrove platforms with substantial elevation capital can undergo considerable vertical losses within the tidal frame before they are converted into tidal flat or open water (Cahoon et al., 2019; Lovelock et al., 2015). Furthermore, a range of processes that include sediment oxidation and compaction, ponding and pond expansion, and marsh-edge erosion (e.g., Day et al., 2011; Mariotti & Fagherazzi, 2013; Ortiz et al., 2017; Törnqvist et al., 2008; Wilson & Allison, 2008; Zoccarato et al., 2018) often take longer (i.e., at least multidecadal timescales) to fully develop. Put differently, despite these detrimental processes coastal wetlands possess the ability to withstand RSLR for a while, even when they face eventual collapse. Such a collapse may be very rapid.

Viewed more broadly, such behavior is consistent with the widely observed nonlinear response of ecosystems to external stressors (Scheffer et al., 2001). A wide range of studies on coastal wetlands has demonstrated similar phenomena, that is, nonlinear (e.g., Marani et al., 2007) or lagged (e.g., Kirwan & Murray, 2008) responses to accelerated RSLR. The role of elevation capital within this context is critical: for example, the tight connection between salt marsh elevation and resilience is now well documented (e.g., Ganju et al., 2020).

In conclusion, coastal wetlands may hold their ground over short time scales and then suddenly collapse, depending on elevation capital or tidal range, primary productivity, and RSLR (Figure 2). In the case of marshes, instruments focused high in the tidal frame would likely see a marsh gaining elevation at the rate of RSLR. However, this can only happen at relatively modest rates of RSLR. At these high elevations, an increasing rate of RSLR raises productivity (Figure 2a) and biogenic accretion (Figure 2b), which maintains equilibrium. Hence, the marsh can persist over a wide range of low to modest rates of RSLR—more so in macrotidal settings and less so in microtidal settings—because RSLR must approximately equal the tidal amplitude to move the marsh from the upper limit to the point of collapse. As the rate of RSLR continues to increase, the equilibrium elevation first slowly and then rapidly decreases as the marsh moves to an unstable state (Figure 2c). In the unstable state, continued increase in RSLR decreases production and biogenic accretion, and the marsh falls behind rather quickly, eventually drowning. In short, marshes will survive until the elevation capital is exhausted.

Even with rapidly accelerating global sea-level rise, coastal wetlands are unlikely to disappear entirely. A striking illustration is provided by the stratigraphic record from the Mississippi Delta where during the early Holocene, when rates of RSLR approached 10 mm yr^{-1}, incipient (or fringing) marshes only a few kilometers wide rapidly migrated landward with rising sea level. This resulted in thin marsh strata (typically a few decimeters or less) that quickly drowned and were overlain by open-water (lagoonal) deposits (Törnqvist et al., 2020). Only when RSLR decelerated to rates <3 mm yr^{-1}~7,000 years ago, the Mississippi Delta as we know it today started to form by means of rapid shoreline progradation (on the order of 100–150 m yr^{-1}; Chamberlain et al. [2018]) and associated marsh expansion, echoing delta initiation on a global scale around this time (Stanley & Warne, 1994). Present-day examples of extensive marsh from a proximal portion of the Mississippi Delta and fringing marsh from a more distal setting are illustrated in Figure 3. These differences correspond to coastal prisms of different sizes illustrated in Figure 1.

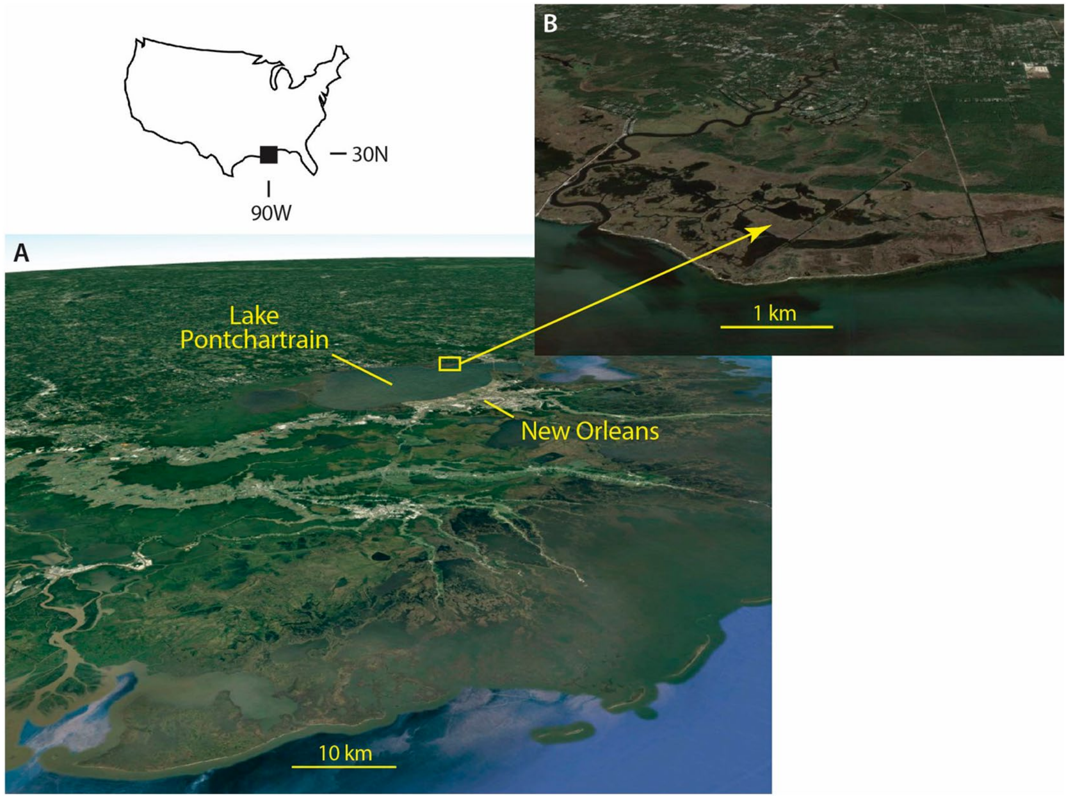

Figure 3. Oblique images illustrating (a) a view to the northeast across the Mississippi Delta with extensive marshland in the foreground, relatively close to a major sediment source (the Atchafalaya River) and (b) fringing marsh north of Lake Pontchartrain that is much more isolated from the sediment source. Source: Google Earth Pro.

The ability of stratigraphic models of coastal wetland evolution to make meaningful predictions depends on a variety of detailed field observations that straddle a range of timescales—including both paleo-records and instrumental data—as discussed at more length in the next section.

4. A Path Forward

The advances outlined above offer new prospects for predicting the future trajectory and fate of global coastal wetlands. Complementing the recent contribution by Fagherazzi et al. (2020), we highlight a few salient topics that are particularly relevant to maximize the potential of stratigraphic models of coastal wetland evolution. First of all, more paleo-records of coastal wetland change are needed to sample the rich variability of wetland response to RSLR that in all likelihood has not yet been fully captured. However, the effectiveness of coastal wetland modeling also hinges on more sophisticated field observations in modern marshes and mangroves. Future work is now poised to take advantage of (1) improved digital elevation models (DEMs); (2) hitherto underutilized sediment flux data; and (3) the increasing availability of monitoring systems of present-day coastal wetland change. First, DEMs combined with projections of RSLR define the space that needs to be filled (i.e., accommodation) for wetlands to keep up with RSLR and to maintain elevation capital. Second, the sediment flux from the continents to the oceans sets the ultimate boundary condition of how much sediment is potentially available to fill this space, whether directly from suspension or indirectly from resuspension of marine deposits. And third, monitoring wetland change plays a pivotal role in determining whether coastal wetlands are presently tracking RSLR. We close by discussing how these data sources can be merged within a modeling framework to spur future progress.

DEMs for LECZs are improving rapidly. In the past, DEMs have commonly been produced from radar data collected during the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). For example, an assessment of the vulnerability of the world's major deltas (Syvitski et al., 2009) relied on SRTM data, as did the projections of the future of global coastal wetlands by Schuerch et al. (2018). However, SRTM data are not well suited to determine elevations within LECZs, where decimeter-scale rather than meter-scale accuracy is needed to examine the effects of RSLR within the next century (Gesch, 2018; Kulp & Strauss, 2019). For example, the Sundarbans mangroves in the Ganges-Brahmaputra Delta (Bangladesh and India) exhibit SRTM elevations >10 m above sea level, a consequence of incomplete penetration of the radar signal into forested areas (Hofton et al., 2006). A comparison of SRTM and Light Detection and Ranging (LiDAR) data from LECZs in the conterminous United States revealed root mean square errors for geodetically ground-truthed elevations of 5.57 and 0.72 m, respectively, although this number is in many cases closer to 0.10–0.19 m for LiDAR data (Gesch, 2018). While LiDAR data are increasingly common, they are still largely unavailable in less wealthy countries. As a result, SRTM data remain important. Recent attempts to reduce the bias in SRTM data have resulted in CoastalDEM (Kulp & Strauss, 2019) that utilizes neural networks to roughly cut the SRTM error in half. While this still falls short of the preferred sub-meter accuracy, it offers promise for more refined modeling of coastal wetland change, although validation outside of the United States and Australia remains an important priority. Overall, the efforts to refine DEMs have typically led to a reduction of elevations in LECZs, as exemplified by a mean elevation in the Mekong Delta (Vietnam) that has been shown to be almost 2 m lower than previously assumed (Minderhoud et al., 2019). Such corrections have major implications for stratigraphic models of coastal wetland evolution; reduced elevations greatly increase the accommodation that needs to be filled with sediment to maintain viable wetlands with adequate elevation capital.

While coastal wetlands may partly depend on sediment from nearby marine environments, they are ultimately fed from the continents by rivers. Global, distributed data sets on sediment fluxes have become increasingly available in the past two decades, based on a combination of observations from monitoring stations near river mouths that capture the sediment flux from entire drainage basins, and hydrologic modeling to extrapolate these point observations to drainage basins that lack direct measurements (Syvitski et al., 2005). A recent decline of the riverine sediment supply has been demonstrated both at the continental (Weston, 2014) and the global (Syvitski et al., 2005) scale. The worldwide decline from comparatively pristine to anthropogenically disturbed sediment fluxes (primarily due to damming) is about 15% (Syvitski & Kettner, 2011), although sand supply may be sustained by enhanced channel-bed degradation downstream of dams (Williams & Wolman, 1984). With more dams planned globally (Zarfl et al., 2015) as well as attempts to reduce soil erosion rates (Montgomery, 2007) that may well expand in the future, it is unlikely that the decline in sediment delivery will be reversed (Dunn et al., 2019).

The A/S stratigraphic modeling approach, adapted to also capture biogenic accretion, offers excellent potential for progress in the modeling of coastal wetland evolution. There are still significant hurdles to be taken, however. Chief among them is the dilemma of the partitioning of sediment between terrestrial and marine environments, as reflected by the sediment trapping efficiency in the coastal zone (i.e., what proportion of the sediment flux that arrives from the continental interior is sequestered in the LECZ). It is well established that sediment trapping efficiency varies widely between different source-to-sink systems (e.g., 30%–70%; Blum and Roberts [2009]) and more recent studies (Esposito et al., 2017; Xu et al., 2019) have shown that trapping efficiency within a single delta can range from 5% to 100%, depending on the specific location on the delta plain. The situation is even more challenging in non-deltaic coastal wetlands where sediment pathways are considerably more complex. Clearly, this is a non-trivial problem.

Comprehensive and systematic monitoring of coastal wetland change, both lateral and vertical, is among the most basic and critical needs. In addition to the widespread space-based methods that can be employed within this context (e.g., Couvillion et al., 2017; Donchyts et al., 2016; Pekel et al., 2016), the proliferation of the surface-elevation table—marker horizon (SET-MH) method (Cahoon, 2015; Cahoon et al., 2020; Webb et al., 2013) plays a critical role in understanding the vertical dimension of change (i.e., surface-elevation change, vertical accretion, and shallow subsidence). SET-MH monitoring holds an important key to determining whether coastal wetlands keep up with RSLR, although the interpretation of these data must be done with care (Wasson et al., 2019). The expanding network of such wetland observations is seen in mangroves in the Indo-Pacific region (Lovelock et al., 2015) as well as in marshes along the US Gulf Coast (Osland et al., 2017). This latter area includes coastal Louisiana, where the Coastwide Reference Monitoring System (CRMS) (Steyer et al., 2003) has been operational since 2005. This system consists of nearly 400 monitoring sites, the vast majority equipped with a SET-MH station, and has enabled considerable advances in understanding the relationship between wetland health, accretion patterns, shallow subsidence, and sediment budgets (Jankowski et al., 2017; Sanks et al., 2020). The CRMS data extend far beyond SET-MH measurements and include systematic monitoring of a wide range of other environmental parameters (mainly associated with vegetation, soils, and hydrology) and they are publicly available (https://www.lacoast.gov/crms/Home.aspx). The potential of SET-MH monitoring systems is vast, given the low cost of installation (Webb et al., 2013) and the modest density of stations needed to produce meaningful results (Keogh & Törnqvist, 2019; Lynch et al., 2015).

The integration of field observations with models will remain key to future progress (e.g., Wiberg et al., 2020) and given the discussion above, it is critical that coastal wetland models conserve mass (e.g., Mariotti, 2020). Continued progress will require synergy between short-term instrumental records that often break down component ecogeomorphic processes, and the long-term stratigraphic record that lacks this detail but offers powerful insights into the eventual outcomes of the interplay between RSLR and coastal wetland evolution. Akin to climate models that are routinely validated by means of the paleoclimate record, constraints provided by the geologic record of marshes and mangroves should be satisfied by the next generation of coastal wetland evolution models. We anticipate that this may lead to substantially different—and less optimistic—model predictions than those that have recently been proposed.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

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