SPECIAL ISSUE: WETLAND ELEVATION DYNAMICS



Accelerating Elevation Gain Indicates Land Loss Associated with Erosion in Mississippi River Deltaic Plain Tidal Wetlands

Camille LaFosse Stagg¹ · Leigh Anne Sharp² · Emily Fromenthal³ · Brady Couvillion¹ · Victoria Woltz³ · Sarai Piazza¹

Received: 28 July 2023 / Revised: 11 December 2023 / Accepted: 18 December 2023 / Published online: 22 January 2024 This is a U.S. Government work and not under copyright protection in the US; foreign copyright protection may apply 2024, corrected publication 2024

Abstract

In recent years, the Mississippi River Deltaic Plain (MRDP) has experienced the highest rates of wetland loss in the USA. Although the process of vertical drowning has been heavily studied in coastal wetlands, less is known about the relationship between elevation change and land loss in wetlands that are experiencing lateral erosion and the contribution of erosion to land loss in the MRDP. We quantified relationships of elevation change and land change in ten submerging tidal wetlands and found that, despite significant land loss, elevation trajectories in seven of the land loss study sites were positive. Furthermore, we observed an acceleration in elevation gain preceding the conversion from vegetated marsh to open water.

To identify regional contributions of lateral erosion to land loss, we quantified the relationship of elevation change and land change in 159 tidal marsh sites in the MRDP. Approximately half the sites were persistently losing land, and 82% of these sites were vulnerable to erosion, identifying erosion as a dominant mechanism of coastal wetland loss in this region. Notably, the sites that were vulnerable to erosion were experiencing land loss while also gaining elevation, and sites with the highest land loss exhibited accelerating elevation gain. Together, these data illustrate that (1) erosion is a dominant mechanism of wetland loss in the MRDP, (2) accelerated elevation gain is an indicator of erosion, and (3) consideration of elevation change trajectories within the context of land change is critical for providing accurate coastal wetland vulnerability assessments.

Keywords Lateral erosion · Vertical drowning · Surface elevation change · Edge retreat · Coastal land loss · Tidal wetlands

Introduction

Coastal wetlands around the world are disappearing as climate and land use stressors continue to impact these ecosystems (Lotze et al. 2006). In recent years, Louisiana has experienced more loss of coastal herbaceous wetlands to open water than any other state in the contiguous USA (NOAA, 1996; 2016). Many processes can contribute to wetland loss, including excessive flooding from rising sea levels

Communicated by Just Cebrian

- ² Louisiana Coastal Protection and Restoration Authority, Lafayette, LA 70506, USA
- ³ Cherokee Nation System Solutions Contractor in Support of U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA 70506, USA

(Morris et al. 2002; Kirwan et al. 2010), extreme climate events (Osland et al. 2020; Lovelock et al. 2021; Stagg et al. 2021), and hydrologic alteration, among others (Edmonds et al. 2023). Researchers have been investigating causes of wetland loss for decades, and, excluding direct removal of wetlands (Turner 1997; Pendelton et al., 2012), have identified two primary mechanisms that control coastal wetland loss: vertical drowning and lateral erosion.

Vertical drowning, or peat collapse, is the slow sinking of the wetland surface below the water, effectively converting the vegetated wetland to open water (Reed 1995; Chambers et al. 2019). Submergence results from a disruption in the biophysical feedbacks between flooding, plant production and sediment accretion that otherwise allow wetlands to maintain their relative elevation within the tidal frame (Morris et al. 2002; Kirwan and Megonigal 2013). Flooding is a key regulator of wetland health, but excessive flooding can lead to declining plant growth and organic matter accumulation, which promotes elevation loss or shallow subsidence (Nyman et al. 1993; Stagg et al. 2020).

A robust body of research provides a detailed understanding of shallow subsidence in coastal wetlands (reviewed in

Camille LaFosse Stagg staggc@usgs.gov

¹ U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA 70506, USA

Cahoon et al. 2020), which is the downward movement of the wetland surface relative to an established benchmark or datum as influenced by subsurface processes (Cahoon et al. 2002). The surface elevation table-marker horizon (SET-MH) method, developed to quantify contributions of surface and subsurface processes to wetland elevation change, has been used across the globe in both temperate and tropical regions to evaluate elevation dynamics in coastal marshes (Webb et al. 2013; Raposa et al., 2016; Kirwan et al. 2016; Feher et al. 2022). Assessments of coastal wetlands worldwide have illustrated that subsidence is an important contributor to submergence of coastal wetlands (Cahoon et al. 2006; Kolker et al. 2011; Jankowski et al. 2017). However, the vulnerability of wetlands that are gaining elevation is still unclear (Kirwan et al. 2016; Saintilan et al. 2022), emphasizing the need for a better understanding of additional mechanisms contributing to coastal wetland loss (Fagherazzi et al. 2013).

Lateral processes are critical to marsh resilience (van de Koppel et al. 2005; Mariotti and Fagherazzi 2013; Mariotti 2020), and marsh edge erosion is a principal driver of wetland retreat in coastal wetlands around the world (Morton et al. 2009; Leonardi et al., 2016). Lateral erosion is primarily controlled by waves, including wind-waves and boat wakes, which impact the marsh edge and remove material from the marsh surface, as well as below the surface along the escarpment (Fagherazzi et al. 2007; Houser 2010; Mariotti and Fagherazzi 2010). Tidal current, wetland surface elevation, water level, and wetland soil and vegetation characteristics also influence the rate of erosion (Wang et al. 2020; Valentine and Mariotti 2019). Furthermore, erosion can occur in interior wetlands, where it is characterized by the expansion and deepening of interior ponds (Luk et al. 2023) and the formation of amorphous ponds and edge retreat following hurricanes and major storm events (Morton and Barras 2011).

Despite a growing awareness of the important contributions of lateral erosion to coastal wetland land loss (Fagherazzi et al. 2013; Ganju et al. 2017), and the inclusion of both vertical and lateral processes in marsh evolution models (Mariotti and Carr 2014; Valentine and Mariotti 2019; Mariotti 2020; Ganju et al. 2023), data characterizing the change in wetland elevation during an erosional land loss event, i.e. the conversion from vegetated wetland to open water, is extremely limited (but see Feagin et al. 2009; Steinmuller et al. 2022; Fig. S5 in Saintilan et al. 2022). The objective of this study was to characterize the relationship between vertical elevation change and lateral erosion in coastal wetlands. We sought to answer the following questions: (1) What is the relationship between wetland surface elevation change and land loss in eroding tidal wetlands? (2) Is elevation change a useful indicator of wetland loss in laterally eroding wetlands? and (3) Is erosion a primary mechanism of land loss in the Mississippi River Deltaic Plain?

Methods

Study Location

The Mississippi River Deltaic Plain was selected as the study area due to the exceedingly high rates of land loss observed in this region, where up to 25% of the original land area has been converted to open water since 1932 (Couvillion et al. 2017). In response to the land loss crisis in coastal Louisiana, the US Congress enacted the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) to fund restoration and protection of the nation's valuable natural resource. The Coastwide Reference Monitoring System (CRMS) was established to assess the impacts of restoration and conservation efforts with CWPPRA funding. The CRMS program provides an exceptional data resource, producing standardized ecological and environmental data for approximately 390 coastal wetland sites since 2006 (https://www. lacoast.gov/crms/Home.aspx). In addition to continuous hydrologic data and species-level annual vegetation surveys, the CRMS program provides long-term marsh surface elevation change data co-located with land cover change assessments, allowing us to characterize the relationship between elevation change and land loss.

To characterize mechanisms of land loss in tidal Mississippi River Deltaic Plain wetlands, we quantified relationships between land change and elevation change in focal land loss study sites where elevation data was available during the conversion from vegetated wetland to open water. Land loss study sites (n = 10) were selected based upon the following criteria: must be tidally connected (tidal amplitude > 0 m; Fig. S1) and must have complete and persistent land loss within the elevation change data collection area (SET-MH stations) during the study period (2008–2018) (Fig. 1). Of the ten land loss study sites, eight sites were prime examples of erosion. Aerial imagery analysis (Couvillion 2021) and visual observations (https://cims.coastal.la.gov/DataDownload/ DataDownload.aspx?type=surface_elevation) from these eight land loss study sites (Data S1) recorded lateral transgression of the adjacent water body that eventually expanded into the RSET stations (Fig. 2), providing a direct measure of elevation change during the transformation from vegetated wetland to open water (Fig. 3). Additionally, we identified relationships between elevation change and land change in 159 sites across the Mississippi River Deltaic Plain to develop a land-change classification system. Tidal wetland sites included in the analyses were located in various geomorphic settings representing active and abandoned phases of the delta cycle, with high riverine sediment deposition contributing to rapid growth and relative stability in active deltaic settings, and low sediment deposition and subaerial deterioration in abandoned deltaic settings



Fig. 1 Location of tidally influenced coastal Louisiana marshes in the Mississippi River Deltaic Plain. Red triangles represent 10 land loss study sites (CRMS0174, CRMS0176, CRMS0121, CRMS0302, CRMS0315, CRMS0347, CRMS0355, CRMS0376, CRMS0489, and CRMS0545). All sites identified here are part of the Coastwide Refer-

(Roberts 1997). The 159 CRMS sites were included in the analysis based on the following criteria: non-floating, herbaceous, tidally influenced (tidal amplitude > 0 m, http://cims. coastal.louisiana.gov), and located within the Mississippi River Deltaic Plain (Fig. 1).

Data Collection and Analysis

All data analyzed in this manuscript, including tidal amplitude, land area change, and elevation change were acquired from the publicly available CRMS program website (CPRA 2023). All data collection protocols are available in Folse et al. (2020) unless otherwise stated.

ence Monitoring System (Coastal Protection and Restoration Authority (CPRA) of Louisiana 2023. Coastwide Reference Monitoring System. Coastal Information Management System (CIMS) database. https://cims.coastal.la.gov. Accessed 08 March 2023)

Land Change

We used land change matrices of aerial imagery published for each CRMS site (Couvillion 2021) to calculate land area change during the study period (2008 to 2018) (Data S1). Land area change was calculated as the amount of land lost (land converted to water) or land gained (water converted to land) as a proportion of the original 2008 land cover area in the 1-km² CRMS site boundary. Land change matrix classes captured persistent land change as well as ephemeral, or oscillating, areas that both gained and lost land area over the study period. Uncertainty in land change values was estimated as oscillating area, which was summed to quantify the total area that was oscillating between 2008 and 2018.





Fig. 2 Land change matrix at CRMS Site 302, illustrating lateral erosion from the adjacent water body resulting in persistent land loss (shown in a red-yellow color ramp) during 2005–2018. Photos highlight observed erosion and conversion to open water at CRMS0302. Photos show (a) vegetated wetland in Spring 2012 in contrast to

(**b**) open water in Spring 2016. (Coastal Protection and Restoration Authority (CPRA) of Louisiana 2023. Coastwide Reference Monitoring System- Land Change Matrix modified from (Beck et al. 2021). Photo credit: CRMS, public domain

If persistent land gain or loss was less than total oscillating land change, sites were classified as oscillating, and land change trajectories were not interpreted.

Elevation Change and Acceleration

Surface elevation change was measured at CRMS sites using the rod surface elevation table (RSET) methodology established by Cahoon et al. (2002). Establishment of RSET benchmarks at ~ 300 CRMS sites occurred in 2006–2008. For purposes of these analyses, the benchmark establishment date, or baseline, was set to 2008. Detailed protocols for RSET benchmark establishment and data collection at the CRMS sites is available in Folse et al. (2020). From the RSET benchmark, surface elevation was measured at least annually from nine points in each of four cardinal directions. For every sampling event, mean elevation change was calculated for each of the four cardinal directions, and a single elevation change rate was calculated using linear regression of elevation change over time (mm y⁻¹) for each RSET benchmark (Cahoon et al. 2002; Data S1). To determine the change in elevation rate, an elevation



Fig. 3 Time-series photos illustrating the relationship between surface elevation change and erosion of the selected land loss study site CRM0302. (**A**) Wetland surface elevation (mm) of land loss study site CRMS0302 spanning the transition from vegetated wetland to open water. The red dotted line denotes the conversion of vegetated wetland to open water within the SET-MH station, which occurred in Fall 2015. Gray shading/lower-case letters correspond to SET-MH

photos in panel B. (**B**) Photos of SET-MH station in land loss study site CRMS0302 illustrating (**a**) a vegetated wetland in Spring 2015, (**b**) significant loss of vegetation in Fall 2015, and (**c**) complete conversion to open water in Fall 2016. Site CRMS0302 was subsequently destroyed by Tropical Storm Cindy in 2017 and removed from the CRMS data collection network. Photo credit: CRMS, public domain

acceleration rate (mm y⁻²) was calculated as the change in the annual elevation change rate (mm y⁻¹) over time (y) (Data S1, S2). Following benchmark establishment, at least 5 years of data were required to calculate the initial annual elevation change rate (Lynch et al. 2015); therefore, in the elevation acceleration analysis, a single elevation change rate was calculated for the period 2008–2013, after which elevation change rates were calculated annually until 2021. Additionally, in the ten land loss study sites, where complete land loss occurred in the SET-MH sampling area,

the period of record used to calculate elevation change was shortened to include data collected only while the RSET station was vegetated, preceding the conversion to open water (Table S1). Linear regressions were used to calculate elevation change rates (mm y⁻¹) and acceleration rates (mm y⁻²), which represent an approximation of the average rate and derivative, respectively, over the period of record. All analyses were performed in JMP statistical package (JMP[®], Version 13.2.1. SAS Institute Inc., Cary, NC, USA, 1989–2021) (Table S1).



Fig. 4 Conceptual model of criteria used to define the five land change mechanisms based upon land change and elevation change trajectories. Positive trajectories (+) represent land gain and elevation gain. Negative trajectories (-) represent land loss and elevation loss. Oscillating sites are represented by both positive and negative (+/-) land change trajectories

Land Change Mechanism Classification

Using the elevation change and land change trajectories, we defined five discrete mechanisms of land change (oscillating, land building, vertical drowning, lateral erosion, and recovering) for all tidal herbaceous wetlands in the Mississippi River Deltaic Plain (n=159; Fig. 4; Table 1). Elevation change was classified as gaining (positive) or losing (negative) elevation based upon the overall elevation change rate (mm y⁻¹) for the site. Further refinement of the elevation change classification was based upon acceleration rates (mm y⁻²), increasing (accelerating), decreasing (decelerating), or no trend (estimated using linear regression fit statistics $R^2 < 0.1$, Data S1). Land change was classified as gaining (positive), losing (negative), or oscillating (positive/negative) land based upon the persistent net change in land cover from 2008 to 2018. Land building was defined by land gain and elevation gain. Vertical drowning was defined by a combination of land loss and elevation loss, whereas lateral erosion was defined by a combination of land loss and elevation gain. Recovering was defined by land gain and elevation loss. Sites with no clear acceleration trend ($R^2 < 0.1$) were not assigned land change mechanisms (= N/A, Table 1).

Results

Land Change

Nearly half of all tidal marsh sites in the Mississippi River Deltaic Plain, 47% (74 sites), experienced persistent land loss between 2008 and 2018 (Fig. 5). Persistent land gain was observed in only 14% of the region (22 sites), and the remaining 40% (63 sites) had oscillating land change, with both land gains and land losses over the period of study. Land change at sites with persistent land loss ranged between -2% and -80% during 2008–2018 (Fig. 5). The ten land loss study sites, which were selected following observed persistent land loss at the site level (Fig. 5).

Elevation Change

Most tidal marshes in the Mississippi River Deltaic Plain, 94% (149 sites), had positive elevation trajectories, or elevation gain, and less than 6% of the region (10 sites) had

Table 1 Land change	La
mechanisms defined by unique	
combinations of land change	
rajectory, elevation change	
rajectory, and elevation change	
acceleration (Fig. 4). Number	La
of sites in each class (N sites,	
% of Region) quantified from	
he total 159 tidal marsh sites	
n the Mississippi River Deltaic	
Plain. Sites with no clear	
acceleration trend ($R^2 < 0.1$)	00
were not assigned land change	05
mechanisms (N/A)	

Land change	Elevation change	Mechanism	Ν	% of Region	Ν
			Sites		Land Loss
					Study Sites
Land Gain	Accelerating Elevation Gain	Land Building	10	6	0
	Decelerating Elevation Gain	Land Building	6	4	0
	Decelerating Elevation Loss	Recovering	2	1	0
	Accelerating Elevation Loss	Recovering	0	0	0
	No Acceleration Trend	N/A	4	3	0
Oscillating Land	Accelerating Elevation Gain	Oscillating	31	19	0
	Decelerating Elevation Gain	Oscillating	20	13	0
	Decelerating Elevation Loss	Oscillating	1	1	1
	Accelerating Elevation Loss	Oscillating	0	0	1
	No Acceleration Trend	N/A	11	7	0
Land Loss	Accelerating Elevation Gain	Lateral Erosion	33	21	2
	Decelerating Elevation Gain	Lateral Erosion	27	17	2
	Decelerating Elevation Loss	Vertical Drowning	3	2	0
	Accelerating Elevation Loss	Vertical Drowning	5	3	3
	No Acceleration Trend	N/A	6	4	0

Fig. 5 Relationship between land change (y-axis) and wetland surface elevation change (x-axis) in 159 tidal marshes across the Mississippi River Deltaic Plain. Triangles represent the land loss study sites, while diamonds represent sites that are oscillating. Open symbols represent marshes in active delta settings



negative elevation trajectories over the period 2008–2021 (Fig. 5). Of the 149 sites gaining elevation, only 13% (20 sites) had persistent land gain, and half of these sites were located within active deltaic settings (Fig. 5, top right quadrant). Remarkably, most sites with persistent land loss had positive elevation trajectories. Only 11% of sites (8 sites) with persistent land loss had negative elevation trajectories (Fig. 5, bottom left quadrant), and the majority of sites with persistent land loss had positive elevation trajectories (90%, 67 sites) (Fig. 5, bottom right quadrant).

Elevation Change Acceleration

In all the eroding land loss study sites, including those with slowing elevation gain, marsh surface elevation increased prior to a dramatic decline in elevation associated with conversion to open water, or persistent wetland loss (Fig. 3; Fig. 6; Data S1). Furthermore, in several eroding land loss study sites we observed a positive acceleration in elevation gain preceding the conversion from vegetated marsh to open water (Fig. 6).

Fig. 6 Rate of annual wetland surface elevation gain (y-axis) over time (x-axis) in land loss study sites with sufficient data to calculate acceleration (mm y^{-2}). Positive acceleration rates represent faster elevation gain over time, and negative acceleration rates represent slowing elevation gain over time. Elevation change rates were estimated using data from the vegetated marsh only, during the period preceding land loss in the SET-MH station (Table S1)



Elevation Change Acceleration



Land Change Mechanisms

We quantified elevation change acceleration for all tidal marshes in the Mississippi River Deltaic Plain and found that almost half of the tidal marshes, 47%, are gaining elevation at an increasing rate (75 sites, Fig. 7). In tidal marshes with increasing rates of elevation gain, most sites had persistent land loss, including sites with the highest rates of land loss in the region (Fig. 7, top right quadrant). Very few tidal marshes had accelerated elevation gains along with land gains, and the majority of these sites were located in the active Atchafalaya and Belize Deltas (Figs. 7–8). These data illustrate that land gain is restricted to active delta settings, and accelerated elevation gains are predominantly associated with land loss.

Of the 74 sites with persistent land loss, less than 10% (8 sites) were classified as vertical drowning. In contrast, the majority of land loss sites, 82%, were classified as lateral erosion. Results from this analysis clearly illustrate that lateral erosion is currently the dominant mechanism of land loss in the Mississippi River Deltaic Plain and highlight the need to interpret land change and elevation change in tandem in coastal Louisiana (Fig. 8).

Discussion

Recent research highlights a disconnection between vertical elevation change and lateral erosion processes in current wetland evolution and land loss assessments (Mariotti and Fagherazzi 2010; Ganju et al. 2023). Similar to our results, Steinmuller et al. (2022) observed rapid marsh loss associated with lateral erosion as marshes simultaneously gained elevation. In fact, several numerical models have described a scenario in which the wetland surface maintains vertical equilibrium with sea-level rise as the unstable marsh boundary retreats (Mariotti and Fagherazzi 2010; Tambroni and Seminara 2012; Mariotti and Carr 2014). Yet few studies have measured the change in marsh elevation during an erosional land loss event. The current study of 159 tidal marshes in Mississippi River Deltaic Plain reveals that eroding marshes not only gain elevation but also have a unique elevation signature, accelerated elevation gain, that, outside of active delta settings, indicates impending wetland loss.

In the current study sites with accelerated elevation gains, increases in elevation were driven by high rates of surface accretion (Fig. S2). It is possible that accelerated accretion was tracking increasing rates of sea-level rise (Weston et al.



Fig. 7 Relationship between elevation change (y-axis), elevation acceleration (x-axis), and land loss (color ramp) in 159 tidal marshes across the Mississippi River Deltaic Plain. Triangles represent the land loss study sites, and diamonds represent sites that are oscillating.

Open symbols represent marshes in an active delta setting. Land loss is represented by negative land cover change values (yellow, orange and red), and land gain is represented by positive land change values (blue and purple)



Fig.8 Map of five land change mechanisms identified in 159 tidal marsh sites within the Mississippi River Deltaic Plain. Land change mechanisms were defined by land change trajectory, elevation change

trajectory, and elevation acceleration (Table 1). Land loss study sites are denoted by triangles, and sites located within an active delta are represented by open symbols

2023); however, accretion rates observed during the study period (2008-2021) exceeded contemporaneous rates of relative sea-level rise (RSLR) estimated for this region by Yin (2023) (RSLR = 12.9 mm y⁻¹, period = 2010–2022; Fig. S2). These results suggest that accelerated rates of accretion are due to increased availability of sediment (Kirwan et al. 2010; Fagherazzi et al. 2012), derived from resuspended soils eroded from the adjacent marsh edge (Hopkinson et al. 2018). The ensuing deposition of eroded material forms a natural levee ridge along the retreating edge that appears as accelerated elevation gain in the elevation change record. While sediment transfer from the eroding edge prevents drowning of the more interior marsh (Schepers et al. 2020), this provides a false perception of stability, as the sediment source is autochthonous (i.e., cannibalized from the system; Mariotti and Carr 2014; Ganju et al. 2015; Edmonds et al. 2023). Furthermore, as the edge continues to retreat, the levee ridge, or transgressive berm, will migrate inland until the entire SET-MH station is converted to open water, resulting in an abrupt decline in elevation (Saintilan et al. 2022). Thus, the accelerated gain immediately preceding the erosional land loss event is a pre-cursor to marsh loss and an indicator of wetland vulnerability.

Accelerated elevation gain attributable to subsurface expansion was also observed at some sites (Fig. S2), where the rate of wetland elevation change exceeded rates of accretion. Subsurface expansion has been ascribed to biological processes, such as root growth (McKee, 2007; 2011; Stagg et al. 2016) and physical processes, such as swelling of water-filled pore space in the soil (Nuttle et al., 1990; Cahoon et al. 2011). Subsurface expansion is also an indicator of a floating marsh, which is characterized by a thick floating vegetated mat that detaches from the substrate periodically or floats continuously (Swarzenski et al., 1991). In the current study, subsurface expansion was observed in three sites with persistent land loss. Root mat detachment was confirmed in one of these sites, a land loss study site (CRMS0545), which was floating prior to erosion of the SET-MH station by Hurricane Barry in 2019 (Fig. S3). These results illustrate that not all accelerated elevation gain is associated with erosion, again emphasizing the importance of interpreting elevation change data in the context of historic land area change.

Incorporating observations of land change with elevation change data is critical for providing an accurate assessment of coastal wetland vulnerability. As illustrated in this study, wetland elevation change alone does not adequately capture vulnerability to land loss, because it cannot account for lateral processes that control wetland resilience to sea-level rise (Mariotti 2020). Recent studies have integrated spatial estimates of land change with elevation change data to assess wetland vulnerability (Ganju et al. 2023) and better understand mechanisms of land change (Ganju et al. 2017; Stagg et al. 2020). Yet accurately characterizing persistent land change at many of the study sites in the Mississippi River Deltaic Plain remains challenging.

Wetlands are dynamic ecosystems, adapting to ever-changing environmental conditions associated with tidal flooding, storms, and rising sea levels through sediment accretion and organic matter production (Nyman 1993; Cahoon et al. 2006). Thus, it is not surprising that many of these systems experience both land gains and losses over time as environmental conditions change (Couvillion et al. 2021). We can achieve a greater understanding of long-term trajectories of net land gains and net land losses within the context of geomorphic setting, specifically deltaic setting. Generally, wetlands in active deltas build land, whereas wetlands in abandoned deltas lose land (Fisk et al. 1954; Roberts 1997). Indeed, in the current study, almost all persistent land gain and all land building was limited to sites within the active Atchafalaya River (Wax Lake Delta) and Mississippi River (Belize Delta) deltas. Conversely, we observed that very little land loss was occurring in these active delta sites; rather, 97% of persistent land loss occurred outside of the active deltas. Given that most oscillating sites were not located in the active delta, we expect that land loss will dominate these sites in the future.

To enhance our ability to identify mechanisms of land loss, future studies could incorporate more complex analyses of land change, as presented in Couvillion et al. (2021). Although we chose to use linear estimates of land change to match the temporal scale of the elevation change estimates, future studies could improve the relationships between elevation change and land loss in these oscillating sites by using non-linear analyses (Couvillion et al. 2021; Feher et al. 2022) to capture the non-linear biophysical feedbacks that govern marsh stability (Kirwan and Megonigal 2013; Stagg et al. 2020). Additional land change assessment tools, such as the unvegetated/vegetated marsh ratio (UVVR) developed by Ganju et al. (2017), have been shown to agree well with sediment budgets of coastal marshes, and can be used as robust indicators of wetland vulnerability, accounting for both vertical and lateral process of marsh formation and deformation.

Notwithstanding the more conservative approach of excluding oscillating land change sites, we confirmed persistent land loss in the majority of this region. By integrating spatial assessments of land change data and wetland elevation change, we identified accelerated elevation change in sites with persistent land loss as an indicator of erosion. Based on this definition, our results show that 82% of land loss sites in this region are experiencing erosion. Historically, there has been a strong emphasis on the contribution of vertical drowning to wetland loss in coastal Louisiana (Boesch et al. 1994; Morton et al. 2002; Reed 2002; Day et al. 2007, 2011; Blum and Roberts 2009; Kolker et al. 2011; Jankowski et al. 2017; Blum et al. 2023). Indeed, we observed land loss in all sites with negative elevation trajectories, indicating vertical drowning of these wetlands. However, our results illustrate that erosion is a dominant mechanism of land loss in the Mississippi River Deltaic Plain, and future research that incorporates both lateral and vertical processes is necessary to provide more robust assessments of wetland vulnerability to climate and land use change.

Conclusion

In conclusion, our study reveals that (1) erosion is a dominant mechanism of land loss in the Mississippi River Deltaic Plain, (2) lateral erosion can lead to rapid wetland loss characterized by accelerating elevation gains, and (3) elevation change data alone are not sufficient to assess wetland vulnerability. Assessments that incorporate spatial estimates of land loss are critical for accurately predicting wetland vulnerability to submergence. Future studies that integrate lateral and vertical processes of wetland evolution and loss can help to provide a more robust understanding of wetland vulnerability.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-023-01321-8.

Acknowledgements A task force of federal agencies representing the U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, National Oceanic and Atmospheric Administration, Natural Resource Conservation Service, and Environmental Protection Agency governs CWPPRA and provides oversight to Louisiana Coastal Protection and Restoration Authority and U.S. Geological Survey for the implementation of CRMS. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Funding This work was supported by the Coastwide Reference Monitoring System (CRMS) program, which is funded through the Coastal Wetland Planning Protection and Restoration Act (CWPPRA) and the State of Louisiana.

Data Availability All data analyzed in this manuscript, including tidal amplitude, land area change, and elevation change were acquired from the publicly available CRMS program website (CPRA, 2023). All data

collection protocols are available in Folse et al. (2020) unless otherwise stated.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

- Beck, H.J., B.R. Couvillion, J. Dugas, A. Garber and K. Mouton. 2021. Coastwide Reference Monitoring System (CRMS) 2005, 2008, 2012, 2015/2016 and 2018 land-water matrices: U.S. Geological Survey data release, https://doi.org/10.5066/P9MHMCFS.
- Blum, M.D., and H.H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* 2 (7): 488–491.
- Blum, M., D. Rahn, B. Frederick, and S. Polanco. 2023. Land loss in the Mississippi River Delta: Role of subsidence, global sealevel rise, and coupled atmospheric and oceanographic processes. *Global and Planetary Change* 222: 104048.
- Boesch, D.F., M.N. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad and D.J.P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. Journal of Coastal Research, i–103. http://www.jstor.org/ stable/25735693.
- Cahoon, D.R., B.C. Perez, B.D. Segura, and J.C. Lynch. 2011. Elevation trends and shrink–swell response of wetland soils to flooding and drying. *Estuarine, Coastal and Shelf Science* 91 (4): 463–474.
- Cahoon, D.R., D.J. Reed, J.W. Day, J.C. Lynch, A. Swales, and R.R. Lane. 2020. Applications and utility of the surface elevation table–marker horizon method for measuring wetland elevation and shallow soil subsidence-expansion: Discussion/reply to: Byrnes M., Britsch L., Berlinghoff J., Johnson R., and Khalil S. 2019. Recent subsidence rates for Barataria Basin, Louisiana. Geo-Marine Letters 39: 265–278. Geo-Marine Letters 40: 809–815.
- Cahoon, D.R., J.C. Lynch, B.C. Perez, B. Segura, R.D. Holland, C. Stelly, and P. Hensel. 2002. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. *Journal of Sedimentary Research* 72(5), 734–739.
- Cahoon, D.R., P. Hensel, T. Spencer, D. Reed, K. McKee and N. Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. In Wetlands and natural resource management, ed. J.T.A. Verhoeven, B. Beltman, R. Bobbink, and D. Whigham, vol. 190, 271–292. Ecological studies. Berlin Heidelberg: Springer-Verlag.
- Chambers, L.G., H.E. Steinmuller, and J.L. Breithaupt. 2019. Toward a mechanistic understanding of "peat collapse" and its potential contribution to coastal wetland loss. *Ecology* 100 (7): e02720.
- Coastal Protection and Restoration Authority (CPRA) of Louisiana. 2023. Coastwide reference monitoring system-wetlands monitoring data. Retrieved from Coastal Information Management System (CIMS) database. http://cims.coastal.louisiana.gov.
- Couvillion, B.R. 2021. Coastal wetland area change in the Gulf of Mexico, 1985–2020: U.S. Geological Survey data release. https:// doi.org/10.5066/P9ZQ17ZW.

- Couvillion, B.R., H. Beck, D. Schoolmaster, and M. Fischer. 2017. Land area change in coastal Louisiana (1932 to 2016) (No. 3381). US Geological Survey.
- Day, J.W., G.P. Kemp, D. Reed, D. Cahoon, R. Boumans, J. Suhayda, and R. Gambrell. 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. *Ecological Engineering* 37 (2): 229–240.
- Day Jr, J.W., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, and D.F. Whigham. 2007. Restoration of the Mississippi Delta: lessons from hurricanes Katrina and Rita. *Science* 315(5819), 1679–1684.
- Edmonds, D.A., S.C. Toby, C.G. Siverd, R. Twilley, S.J. Bentley, S. Hagen and K. Xu. 2023. Land loss due to human-altered sediment budget in the Mississippi River Delta. *Nature Sustainability* 1–8.
- Fagherazzi, S., G. Mariotti, P.L. Wiberg, and K.J. McGlathery. 2013. Marsh collapse does not require sea level rise. *Oceanography* 26 (3): 70–77.
- Fagherazzi, S., C. Palermo, M.C. Rulli, L. Carniello and A. Defina. 2007. Wind waves in shallow microtidal basins and the dynamic equilibrium of tidal flats. *Journal of Geophysical Research: Earth Surface* 112(F2).
- Fagherazzi, S., M.L. Kirwan, S.M. Mudd and G.R. Guntenspergen. 2012. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. *Reviews of Geophysics* 50(1).
- Feagin, R.A., S.M. Lozada-Bernard, T.M. Ravens, I. Möller, K.M. Yeager, and A.H. Baird. 2009. Does vegetation prevent wave erosion of salt marsh edges? *Proceedings of the National Academy* of Sciences 106 (25): 10109–10113.
- Feher, L.C., M.J. Osland, K.L. McKee, K.R. Whelan, C. Coronado-Molina, F.H. Sklar and L. Allain. 2022. Soil elevation change in mangrove forests and marshes of the Greater Everglades: a regional synthesis of surface elevation table-marker horizon (SET-MH) data. *Estuaries and Coasts* 1–30.
- Fisk, H.N., C.R. Kolb, E. McFarlan, and L.J. Wilbert. 1954. Sedimentary framework of the modern Mississippi delta [Louisiana]. *Journal of Sedimentary Research* 24 (2): 76–99.
- Folse, T.M., T.E. McGinnis, L.A. Sharp, J.L. West, M.K. Hymel, J.P. Troutman, D. Weifenbach, W.M. Boshart, L.B. Rodrigue, D.C. Richardi, W.B. Wood, C.M. Miller, E.M. Robinson, A.M. Freeman, C.L. Stagg, B.R. Couvillion and H.J. Beck. 2020. A standard operating procedures manual for the coastwide reference monitoring system-wetlands and the system-wide assessment and monitoring program: methods for site establishment, data collection, and quality assurance/quality control. Louisiana Coastal Protection and Restoration Authority. Baton Rouge, LA. 252.
- Ganju, N.K., M.L. Kirwan, P.J. Dickhudt, G.R. Guntenspergen, D.R. Cahoon, and K.D. Kroeger. 2015. Sediment transport-based metrics of wetland stability. *Geophysical Research Letters* 42 (19): 7992–8000.
- Ganju, N.K., Z. Defne, M.L. Kirwan, S. Fagherazzi, A. D'Alpaos, and L. Carniello. 2017. Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. *Nature Communications* 8 (1): 14156.
- Ganju, N.K., Z. Defne, C. Schwab and M. Moorman. 2023. Horizontal integrity a prerequisite for vertical stability: comparison of elevation change and the unvegetated-vegetated marsh ratio across southeastern USA Coastal Wetlands. Estuaries and Coasts, 1–11.
- Hopkinson, C.S., J.T. Morris, S. Fagherazzi, W.M. Wollheim, and P.A. Raymond. 2018. Lateral marsh edge erosion as a source of sediments for vertical marsh accretion. *Journal of Geophysical Research: Biogeosciences* 123 (8): 2444–2465.
- Houser, C. 2010. Relative importance of vessel-generated and wind waves to salt marsh erosion in a restricted fetch environment. Journal of Coastal Research 26 (2): 230–240.

- Jankowski, K.L., T.E. Törnqvist, and A.M. Fernandes. 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications* 8 (1): 14792.
- Kirwan, M.L., and J.P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 504 (7478): 53–60.
- Kirwan, M.L., G.R. Guntenspergen, A. d'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*. 37(23).
- Kirwan, M.L., S. Temmerman, E.E. Skeehan, G.R. Guntenspergen, and S. Fagherazzi. 2016. Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change* 6 (3): 253–260.
- Kolker, A.S., M.A. Allison, and S. Hameed. 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters* 38(21).
- Koppel, J.V.D., D.V.D. Wal, J.P. Bakker, and P.M. Herman. 2005. Selforganization and vegetation collapse in salt marsh ecosystems. *The American Naturalist* 165 (1): E1–E12.
- Leonardi, N., N.K. Ganju, and S. Fagherazzi. 2016. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. *Proceedings of the National Academy of Sciences* 113 (1): 64–68.
- Lotze, H.K., H.S. Lenihan, B.J. Bourque, R.H. Bradbury, R.G. Cooke, M.C. Kay, and J. Jackson. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312(5781): 1806–1809.
- Lovelock, C.E., R. Reef, and P. Masqué. 2021. Vulnerability of an arid zone coastal wetland landscape to sea level rise and intense storms. *Limnology and Oceanography* 66 (11): 3976–3989.
- Luk, S., M.J. Eagle, G. Mariotti, K. Gosselin, J. Sanderman, and A.C. Spivak. 2023. Peat decomposition and erosion contribute to pond deepening in a temperate salt marsh. *Journal of Geophysical Research: Biogeosciences* 128(2): e2022JG007063.
- Lynch, J.C., P. Hensel, and D.R. Cahoon. 2015. The surface elevation table and marker horizon technique: a protocol for monitoring wetland elevation dynamics (No. NPS/NCBN/NRR—2015/1078). National Park Service.
- Mariotti, G. 2020. Beyond marsh drowning: The many faces of marsh loss (and gain). Advances in Water Resources 144: 103710.
- Mariotti, G., and J. Carr. 2014. Dual role of salt marsh retreat: Longterm loss and short-term resilience. *Water Resources Research* 50 (4): 2963–2974.
- Mariotti, G., and S. Fagherazzi. 2013. Critical width of tidal flats triggers marsh collapse in the absence of sea-level rise. *Proceedings* of the National Academy of Sciences 110 (14): 5353–5356.
- Mariotti, G., and S. Fagherazzi. 2010. A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *Journal* of Geophysical Research: Earth Surface 115(F1).
- McKee, K.L. 2011. Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. *Estuarine, Coastal* and Shelf Science 91 (4): 475–483.
- McKee, K.L., D.R. Cahoon, and I.C. Feller. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* 16 (5): 545–556.
- Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83 (10): 2869–2877.
- Morton, R.A., and J.A. Barras. 2011. Hurricane impacts on coastal wetlands: A half-century record of storm-generated features from southern Louisiana. *Journal of Coastal Research* 27 (6A): 27–43.
- Morton, R.A., N.A. Buster, and M.D. Krohn. 2002. Subsurface controls on historical subsidence rates and associated wetland loss in southcentral Louisiana.

- Morton, R.A., J.C. Bernier, and K.W. Kelso. 2009. Recent subsidence and erosion at diverse wetland sites in the southeastern Mississippi Delta plain. U. S. Geological Survey.
- Nuttle, W.K. 1990. Mechanisms of water storage in salt marsh sediments: The importance of dilation. *Hydrological Processes* 4: 1–13.
- Nyman, J.A., R.D. DeLaune, H.H. Roberts, and W.H. Patrick Jr. 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. *Marine Ecology Progress Series* 269–279.
- National Oceanic and Atmospheric Administration, Office for Coastal Management. 1996. Coastal Change Analysis Program (C-CAP) regional land cover. Charleston, SC: NOAA Office for Coastal Management. Accessed 06/2022 at http://www.coast.noaa.gov/htdata/raster1/ landcover/bulkdownload/30m_lc/.
- National Oceanic and Atmospheric Administration, Office for Coastal Management. 2016. Coastal Change Analysis Program (C-CAP) regional land cover. Charleston, SC: NOAA Office for Coastal Management. Accessed 06/2022 at http://www.coast.noaa.gov/ htdata/raster1/landcover/bulkdownload/30m_lc/
- Osland, M.J., R.H. Day, C.T. Hall, L.C. Feher, A.R. Armitage, J. Cebrian, and C.M. Snyder. 2020. Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality and recovery in North America: refining tipping points for range expansion in a warming climate. *Journal of Ecology* 108(2): 654–665.
- Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, et al. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE* 7 (9): e43542. https://doi.org/10.1371/journal.pone.0043542.
- Raposa, K.B., K. Wasson, E. Smith, J.A. Crooks, P. Delgado, S.H. Fernald, and S. Lerberg. 2016. Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. *Biological Conservation* 204: 263–275.
- Reed, D.J. 1995. The response of coastal marshes to sea-level rise: Survival or submergence. *Earth Surface Processes and Landforms* 20 (1): 39–48.
- Reed, D.J. 2002. Sea-level rise and coastal marsh sustainability: Geological and ecological factors in the Mississippi delta plain. *Geomorphology* 48 (1–3): 233–243.
- Roberts, H. H. (1997). Dynamic changes of the Holocene Mississippi River delta plain: the delta cycle. Journal of Coastal Research, 605–627.
- Saintilan, N., K.E. Kovalenko, G. Guntenspergen, K. Rogers, J.C. Lynch, D.R. Cahoon, and N. Khan. 2022. Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science* 377(6605): 523–527.
- Schepers, L., M.L. Kirwan, G.R. Guntenspergen, and S. Temmerman. 2020. Evaluating indicators of marsh vulnerability to sea level rise along a historical marsh loss gradient. *Earth Surface Processes and Landforms* 45 (9): 2107–2117.
- Stagg, C.L., K.W. Krauss, D.R. Cahoon, N. Cormier, W.H. Conner, and C.M. Swarzenski. 2016. Processes contributing to resilience of coastal wetlands to sea-level rise. *Ecosystems* 19: 1445–1459.
- Stagg, C.L., M.J. Osland, J.A. Moon, C.T. Hall, L.C. Feher, W.R. Jones, and W.C. Vervaeke. 2020. Quantifying hydrologic controls on local-and landscape-scale indicators of coastal wetland loss. *Annals of Botany* 125(2): 365–376.
- Stagg, C.L., M.J. Osland, J.A. Moon, L.C. Feher, C. Laurenzano, T.C. Lane, and S.B. Hartley. 2021. Extreme precipitation and flooding contribute to sudden vegetation dieback in a coastal salt marsh. *Plants* 10(09): 1841.
- Steinmuller, H.E., E. Bourque, S.B. Lucas, K.M. Engelbert, J. Garwood, and J.L. Breithaupt. 2022. Comparing vertical change in Riverine, Bayside, and Barrier Island Wetland soils in response to acute and chronic disturbance in Apalachicola Bay, FL. *Estuaries and Coasts* 1–13.

- Swarzenski, C.M., E.M. Swenson, C.E. Sasser, and J.G. Gosselink. 1991. Marsh mat flotation in the Louisiana delta plain. *The Journal of Ecology* 999–1011.
- Tambroni, N., and G. Seminara. 2012. A one-dimensional eco-geomorphic model of marsh response to sea level rise: wind effects, dynamics of the marsh border and equilibrium. *Journal of Geophysical Research: Earth Surface* 117(F3).
- Turner, R.E. 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. *Estuaries* 20: 1–13.
- Valentine, K., and G. Mariotti. 2019. Wind-driven water level fluctuations drive marsh edge erosion variability in microtidal coastal bays. *Continental Shelf Research* 176: 76–89.
- Wang, P., J.D. Adam, J. Cheng, and M. Vallée. 2020. Morphological and sedimentological impacts of Hurricane Michael along the northwest Florida coast. *Journal of Coastal Research* 36 (5): 932–950.

- Webb, E.L., D.A. Friess, K.W. Krauss, D.R. Cahoon, G.R. Guntenspergen, and J. Phelps. 2013. A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise. *Nature Climate Change* 3 (5): 458–465.
- Weston, N.B., E. Rodriguez, B. Donnelly, E. Solohin, K. Jezycki, S. Demberger, and C.B. Craft. 2023. Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. *Earth's Future* 11(3): e2022EF003037.
- Yin, J. 2023. Rapid decadal acceleration of sea level rise along the US East and Gulf Coasts during 2010–22 and its impact on hurricaneinduced storm surge. *Journal of Climate* 36 (13): 4511–4529.