Tipping points of Mississippi Delta marshes due to accelerated sea-level rise

Torbjörn E. Törnqvist1*, Krista L. Jankowski11, Yong-Xiang Li1,2, Juan L. González1,3

Coastal marshes are threatened by relative sea-level (RSL) rise, yet recent studies predict marsh survival even under the high rates of RSL rise expected later in this century. However, because these studies are mostly based on short-term records, uncertainty persists about the longer-term vulnerability of coastal marshes. We present an 8500-year-long marsh record from the Mississippi Delta, showing that at rates of RSL rise exceeding 6 to 9 mm year−1, marsh conversion into open water occurs in about 50 years. At rates of RSL rise exceeding ~3 mm year−1, marsh drowning occurs within a few centuries. Because present-day rates of global sea-level rise already surpass this rate, submergence of the remaining ~15,000 km2 of marshland in coastal Louisiana is probably inevitable. RSL-driven tipping points for marsh drowning vary geographically, and those for the Mississippi Delta may be lower than elsewhere. Nevertheless, our findings highlight the need for consideration of longer time windows in determining the vulnerability of coastal marshes worldwide.

INTRODUCTION

Landscapes and ecosystems are known to respond in a nonlinear fashion to external stresses (1). Coastal wetlands represent a family of ecosystems that are prone to potentially irreversible collapse because of this mechanism. For example, the productivity of a common coastal marsh grass (Spartina alterniflora) peaks in a distinct elevation range defined by tide levels (2). As a consequence, persistent submergence at a level that exceeds this range (and absent abundant sediment to offset this) will lead to rapid degradation and the conversion of marsh into tidal flat or open water, representing alternative stable states as predicted theoretically (3).

Coastal marshes are among the most valuable ecosystems on the planet (4), yet there is widespread concern about their sustainability due to accelerated sea-level rise and other human-induced stresses. They generally form in the upper half of the intertidal zone and are the result of a delicate balance between vertical accretion and relative sea-level (RSL) rise, driven by a host of physical (e.g., tidal inundation), biological (e.g., plant productivity), and chemical (e.g., decomposition) processes (5–7). Because landward migration of coastal wetlands is increasingly hampered owing to human interference or steep upland slopes (8), marsh survival depends, to a large extent, on surface-elevation gain. However, several studies have shown that even with substantial accretion rates, marshes may be subject to degradation due to sediment compaction (9, 10).

An ensemble of numerical models (11) suggests that threshold rates of RSL rise for marsh survival (generally 10 to 50 mm year−1) are determined mainly by tidal range and suspended sediment concentration (SSC). As a result, several recent studies have advanced the view that marshes may be relatively resilient (12), but inferences like these are, to a large extent, based on observations over annual to decadal time scales only (13).

The Mississippi Delta (MD) experiences some of the highest rates of coastal wetland loss in the world (14). A recent analysis of wetland change at 185 sites across the MD has shown that, over the past decade, vertical accretion has kept pace with the rate of RSL rise (13 ± 9 mm year−1, determined with respect to the wetland surface) at about 65% of these sites (10). However, it remains largely unknown to what extent coastal marshes are sustainable over longer (i.e., multidecadal to centennial) time scales when sediment compaction, ponding, and erosion become significant. The high rates of present-day RSL rise in the MD are not unusual. For example, comparable rates are seen in the Po Delta (15), and even higher rates occur in the Mekong Delta (16). Here, we test the hypothesis that marshes in the MD can keep pace with rates of RSL rise up to 10 mm year−1 by considering marsh records that stretch much of the Holocene. While this empirical approach cannot disentangle all the relevant ecogeomorphic processes and nonlinear feedbacks, it offers direct observational evidence on how their interplay determines marsh survival in the long term.

RESULTS

A high-resolution RSL record for the MD that covers the past 8.5 ka (17) (Fig. 1 and Materials and Methods), combined with detailed facies descriptions from the associated boreholes that were drilled to carry out the sea-level reconstruction (Figs. 2 and 3 and Materials and Methods), enables the evolution of paleo-marshes to be tied directly to rates of RSL rise as determined with respect to the preexisting land surface. The RSL record is based on 72 sea-level index points (SLIPs) derived from compaction-free basal marsh peat—the organic-rich facies that immediately overlie a transgressive wetland paleosol on top of a highly consolidated substrate. Further details about the methodology for sea-level reconstruction can be found elsewhere (18).

Rates of RSL rise (Fig. 1) approach 10 mm year−1 during the earliest phase of the record and then progressively decrease to ~0.5 mm year−1 during the preindustrial millennium (19). As a result, this record enables us to study paleo-marsh response to a wide range of rates of RSL rise as determined with respect to the preexisting land surface. The early portion of the RSL record captures rates predicted...
worldwide for the latter part of the 21st century under the RCP4.5 and RCP8.5 emission scenarios (20).

The stratigraphic analysis focused initially on the 72 sites from which SLIPs were obtained; 15 representative sedimentary logs (10 of which from SLIP sites) are illustrated in Fig. 3. While they mostly feature muddy, organic-rich marsh facies that immediately overlie the paleosol, the subsequent succession varies widely. Specifically, before ~6.8 ka BP (before present; defined as 1950 Common Era), a transition from marsh to lagoonal (i.e., open water) facies with characteristic fauna (commonly the brackish water clam Rangia cuneata) is nearly always present. In contrast, the subsequent portion of the record (<6.8 ka BP) mostly lacks indicators of open-water conditions. Instead, terrestrial facies (predominantly marsh or swamp mud, i.e., including freshwater successions) persist, indicating that vertical accretion kept pace with, or exceeded, the rate of RSL rise. It is important to note that boreholes with comparable basal ages in western and eastern (Fig. 2) portions of the MD exhibit a notably similar stratigraphy (Fig. 3 and figs. S1 and S2).

The analysis was extended by 283 additional boreholes that feature a stratigraphically similar transition (see Supplementary Spreadsheet). Just as the logs discussed above, these sites are scattered more than 100 km apart across the MD and derive from the two study areas that measure 25 to 40 km across (Fig. 2). Because of the large number of observations, spatial variability that inevitably affects smaller areas is therefore filtered out, and the data enable us to extract the broader patterns that characterize this region. Nevertheless, it should be noted that, when examined in more detail, the stratigraphy exhibits a rich variability. This is illustrated by sites with multiple episodes of drowning and return to terrestrial conditions (Fig. 3), demonstrating that other factors, such as the proximity to a sediment source, can be locally important. Each of the borehole logs was classified into fully terrestrial versus drowned facies successions, with the latter (fig. S3) subdivided into gradual or rapid drowning (table S2). About 6.5% of the logs lacked the detail to confidently classify them and were recorded as inconclusive.

Given the tight age-depth relationship (Fig. 1), ages can be assigned to the facies transition at the top of the paleosol in undated boreholes within ~200-year error, enabling the rate of RSL rise with respect to the preexisting land surface to be estimated for each site. The results (Fig. 4) show that when rates are <2 mm year\(^{-1}\), facies successions are always terrestrial. Above this rate, the first drowned sites are encountered. Only when rates of RSL rise exceed 3 mm year\(^{-1}\) does drowning occur in at least 80% of the sites; a small proportion (<10%) remained terrestrial throughout the Holocene. This indicates that, even when rates of RSL rise are very high, local conditions (most likely proximity to a major sediment source) may prevent drowning, but the point is that such conditions are rare. Our findings are robust when viewed separately for the two study areas (fig. S4) or when only relatively thick basal marsh successions are considered (fig. S5), indicating that a rate of RSL rise of 3 mm year\(^{-1}\) represents a threshold rate for marsh drowning in the MD, regardless of marsh maturity.

Before 8.2 ka BP, when rates of RSL rise exceeded 6 to 9 mm year\(^{-1}\), basal marsh facies have a median thickness of only 15 cm (Fig. 3 and Table 1), even after sites with erosional transitions are removed. We refer to these thin strata as incipient marshes (or fringing marshes) with widths of a few kilometers or less, taking into account their

---

Fig. 1. RSL curve and rate of RSL rise in the MD. A total of 72 sea-level index points (SLIPs) from basal marsh peat provides the Holocene RSL history with respect to the compaction-free, (mostly) Pleistocene basement. The location of the study areas is shown in Fig. 2. The gap between ~3.0 and 1.5 ka BP (before present) is merely due to the fact that this time interval was not sampled for \(^{14}\)C dating; it should not be interpreted as a phase with a rate of RSL rise that deviates from the long-term trend. Note also that the youngest SLIP predates the global sea-level acceleration of the past century (not shown in this record). All other (non-SLIP) data points are shown by means of the small black symbols that elucidate the shape of the function that was fitted to the SLIP data. The first derivative of the RSL curve exhibits rates of RSL rise between 8.5 and 0.15 ka BP.

Fig. 2. Distribution of the 355 boreholes across the MD that were used for the paleo-marsh analysis. Note that the distance between the two study areas (A and B) is about 100 km and that boreholes within these two regions are scattered up to 40 km apart. This circumvents sampling bias associated with local conditions that may not be representative for a wider region. The location of the 15 boreholes illustrated in Fig. 3 is shown in orange or red. Base map data: Google, SIO, NOAA, U.S. Navy, NG, GEBCO, Landsat/Copernicus, Terrametrics.
shown for the western and eastern study areas separately (fig. S4) and for basal the nonlinear nature of the marsh response to the rate of RSL rise. Similar plots are

Additional sedimentary logs are shown for the western and eastern study areas separately in figs. S1 and S2.

creases from ~0.5 to 16 adjusted vertically to align the top of the paleosol and arranged with increasing age (and depth) from left to right [in reality, the elevation of the top of the paleosol de-

wetland paleosol to basal Holocene facies and the overlying succession (details about facies units are provided in table S1). For ease of comparison, the logs have been

A selection of 15 representative sedimentary logs features the transition from a

Fig. 3. Characteristic transgressive facies successions from the past 8500 years. A selection of 15 representative sedimentary logs features the transition from a wetland paleosol to basal Holocene facies and the overlying succession (details about facies units are provided in table S1). For ease of comparison, the logs have been adjusted vertically to align the top of the paleosol and arranged with increasing age (and depth) from left to right [in reality, the elevation of the top of the paleosol decreases from ~0.5 to 16 m below North American Vertical Datum of 1988 (NAVD 88); see Supplementary Spreadsheet]. The serrated pattern is used for logs that do not extend all the way to the land surface. For each log, the weighted mean calibrated age (in ka BP) of the basal facies that drape the paleosol and the rate of RSL rise (the first derivative of the equation in Fig. 1) is provided. Directly dated cores are indicated in red; for the other cores, the age of the basal Holocene facies was calculated by means of the equation in Fig. 1. Note that the two logs marked by arrows with largely similar stratigraphy are ~100 km apart (all core locations are shown in Fig. 2). Additional sedimentary logs are shown for the western and eastern study areas separately in figs. S1 and S2.

Fig. 4. Relationship between the rate of RSL rise and marsh persistence. The relative proportion of facies successions (table S2) is determined for eight increments of rates of RSL rise to identify the tipping point for marsh drowning. The abrupt increase in the proportion of drowned sites between 2.5 and 3.0 mm year\(^{-1}\) illustrates the nonlinear nature of the marsh response to the rate of RSL rise. Similar plots are shown for the western and eastern study areas separately (fig. S4) and for basal marsh successions ≥50 cm thick (fig. S5).

original (decompacted) thickness of typically <50 cm (Table 1) and an average seaward slope of the preexisting land surface (i.e., the Pleistocene basement) of about 0.00025 (21). Clearly, these incipient marshes differed strongly from the extensive marshlands that formed later during the Holocene; in addition to the fact that they never fully developed, they occupied a much smaller area. The in-

cipient marshes exhibit rapid drowning, as opposed to the gradual drowning that is more common at sites within the 6.8 to 8.2 ka BP time window where the median thickness of basal marsh facies is 30 to 50 cm (Table 1). While incipient marshes could start to form even under the highest rates of RSL rise seen in our record, they also quickly collapsed.

The duration of marsh persistence for the sites that eventually flooded can be estimated from the thickness of the drowned marsh facies, assuming that vertical accretion initially kept pace with the rate of RSL rise and using a reduction in thickness by a factor of 2.5 due to compaction (22). This estimate suggests (Table 1) that drowning of the incipient marshes before 8.2 ka BP typically occurred in ~50 years or less, while between 8.2 and 6.8 ka BP marshes were able to persist ~300 years on average.

DISCUSSION AND IMPLICATIONS
To what extent is early Holocene marsh evolution relevant to present-day and future conditions? Before the embankment of distributaries and the resulting isolation of the delta plain from clastic sediment input, MD marshes likely enjoyed relatively high SSC values. This is suggested by present-day measurements of up to 150 mg liter\(^{-1}\) during the 2011 flood in Atchafalaya Bay (23)—a setting representative of the large, diffuse plumes associated with the shallow-water lobes that dominated the Holocene MD. However, because of extensive damming in the drainage basin (24), the present-day sediment supply from the Mississippi River is likely lower than it was during the early Holocene. In other words, despite presumably higher sediment availability than the presently observed SSC values, our analysis shows
that early Holocene marshes were unable to keep pace with RSL rise. The microtidal range in this region (presently <0.5 m) limits marsh resilience, but the tidal range was likely higher before 8 ka BP [it has been comparable to the present-day tidal regime since that time (25)]. On the other hand, early Holocene atmospheric CO₂ concentrations were about 65% of present-day values. This may have reduced primary production rates and the organic contribution to marsh accretion (26). On balance, however, early Holocene conditions—a period with no detrimental human impacts—likely favored marsh resilience compared to the present day.

The short-term resilience of MD marshes is illustrated by the fact that they often keep up with the present-day rate of RSL rise of 13 ± 9 mm year⁻¹, as determined with respect to the wetland surface (34). We attribute this difference, at least in part, to the fact that the data-sets that underpin such modeling studies cover short observational sets that underpin such modeling studies cover short observational series (30) where the terrestrial to lagoonal facies contact is less likely to be erosional. Further-more, while the low-elevation MD marshes tend to convert into open water under rapid rates of RSL rise, in other settings with a higher tidal range, this may involve the transformation of high marsh into low marsh (33) or low marsh into tidal flat (8). Nevertheless, we hypothesize that a chief finding of the present study—the large disparity between marsh vulnerability over short versus long time scales—may be generally valid and that the existence of tipping points is a fundamental feature of these ecosystems. The implication of this would be that the associated threshold rates of RSL rise for coastal marsh sustainability may be lower than what studies based on instrumental records suggest. Testing this hypothesis by means of additional studies of paleo-marsh evolution should therefore be a priority for future research. Given the importance to capture the high rates of RSL rise that occurred during the early Holocene, we anticipate that the best targets for this purpose are other large deltas that are most likely to preserve records of this age.

Studies of a wide range of ecosystems have shown that reduced resilience (e.g., due to other, nonclimatic anthropogenic influences) renders them more prone to rapid transformation (1). The severe degradation of MD marshes due to a variety of human impacts, including the dissection of the area by over 15,000 km of canals (14), has already resulted in such a loss of resilience and will make a continued shift to open water more likely. The globally averaged rate of sea-level rise between 2006 and 2015 is 3.58 ± 0.48 mm year⁻¹ (20), and even a best-case scenario in long-term global sea-level projections predicts rates of 5 to 6 mm year⁻¹ for about 2000 years (34). We therefore conclude not only that the 3 mm year⁻¹ threshold rate of RSL rise in the MD has already been crossed but also that this

<table>
<thead>
<tr>
<th>Table 1. Thickness and estimated life span of drowned marsh facies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drowned marsh facies—all sites*</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td><strong>Mostly gradual drowning</strong> (after 8.2 ka BP)</td>
</tr>
<tr>
<td>Median (mean) thickness (m)</td>
</tr>
<tr>
<td>0.30 (0.43)</td>
</tr>
<tr>
<td>Median (mean) life span (years)‡</td>
</tr>
<tr>
<td>212 (282)§</td>
</tr>
<tr>
<td>Number of observations</td>
</tr>
<tr>
<td>51</td>
</tr>
<tr>
<td>Median (mean) thickness (m)</td>
</tr>
<tr>
<td>0.50 (0.58)</td>
</tr>
<tr>
<td>Median (mean) life span (years)‡</td>
</tr>
<tr>
<td>310 (372)§</td>
</tr>
<tr>
<td>Number of observations</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

*All sites (n = 68) that feature lagoonal facies, including those where the contact between terrestrial (usually marsh) and lagoonal facies is erosional. †Selected sites (n = 33) where the terrestrial to lagoonal facies contact is less likely to be erosional. ‡Estimated by correcting the thickness for compaction (a factor of 2.5) and assuming that the accretion rate approximately tracked the rate of RSL rise at the onset of marsh formation. §Note that mean values always exceed median values (typically due to one or a few sites with relatively large numbers); therefore, median values are used in the interpretation.
condition is likely to persist far beyond the time scale of MD marsh drowning. In other words, drowning is inevitable, and conversion back to marsh will be unlikely. This is a major threat not only to one of the ecologically richest environments of the United States but also for the 1.2 million inhabitants (table S4) and associated economic assets that are surrounded by MD marshland. Our findings, viewed within the context of long-term sea-level projections, raise the question whether coastal marshes elsewhere may be more vulnerable than commonly recognized.

**MATERIALS AND METHODS**

**RSL record**

The RSL record was obtained entirely from compaction-free basal peats; paleoenvironments were inferred from δ13C data (18), augmented with information from plant macrofossils (18) and foraminifera (35). Most of the basal peats formed in marshes with brackish to intermediate salinity, i.e., within the intertidal zone. The 72 SLIPs that form the basis for the RSL record were plotted with respect to North American Vertical Datum of 1988 (NAVD 88), in accordance with a previously published synthesis (17). The curve fitting software package TableCurve 2D, version 5.01.02 (www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php) was used to fit and rank 3665 equations to obtain the RSL curve using the central values of the SLIPs ("Sample elevation—base (m NAVD)" and "Calibrated age—weighted mean (cal yr BP)") (17). Because the Holocene RSL history of this region is dominated by glacial isostatic adjustment (peripheral bulge subsidence) as reflected by continuous but progressively decreasing rates of RSL rise (36), we only considered curves characterized by monotonic RSL rise. Subtle, century-scale RSL fluctuations with amplitudes of a few decimeters (19) likely existed, but would have a relatively small impact on the most important portion of our RSL record when rates of RSL rise were the highest (i.e., the effect would be limited to subtle accelerations and decelerations). RSL curves were graphically evaluated and assessed for goodness of fit (R²) and the standard error between the data and the fitted curve. The RSL curve with optimal outcomes with respect to these criteria (Fig. 1) was used to calculate an estimated age of the base of the Holocene succession (i.e., the elevation of the top of the paleosol with respect to NAVD 88) at the 283 sites for which no direct 14C dating was available (for the 72 sites with SLIPs, the calibrated 14C age was used). The associated age error for the sites without direct dating is 213 years, which introduces some uncertainty in the rate of RSL rise at each site.

Within this context, it is important to stress the fundamental difference between the Holocene RSL record from basal marsh facies (mostly basal peat) (Fig. 1) that exhibits rates with respect to the largely compaction-free Pleistocene basement (i.e., the preexisting land surface) and that was used to assess the vulnerability of marshes that formed immediately above this surface, versus present-day rates of RSL rise as determined with respect to the land surface (10). The former provides a robust record of RSL rise that is spatially uniform across the two study areas (Fig. 1). In contrast, the latter rates are much higher (13 ± 9 mm year⁻¹) and spatially variable owing to a combination of factors, including the climate-driven global acceleration of sea-level rise (37), subsurface fluid extraction (38), and high compaction rates (10, 27, 28).

**Borehole data and facies analysis**

The majority of the borehole data (n = 334) were collected by hand, by means of an Edelman auger and a 3-cm-diameter gouge (39). Sediments were described in the field in 10-cm increments, with particular attention to sediment texture, organic-matter content, plant and other fossil remains, color, oxidation state, and sedimentary structures. A smaller number (n = 21) of relatively deep boreholes (typically >12 m) were drilled with a Geoprobe (model 6610 DT) that produced 4-cm-diameter cores that were also described in the field, in a similar way. In many cases, multiple cores were collected at the same site to ascertain that the sampled sections had suffered minimal disturbance (35). No evidence was found for incomplete recovery or sediment compaction due to coring with the Geoprobe. Unlike the hand-drilled boreholes, Geoprobe cores only extended a few meters above the Pleistocene-Holocene transition and therefore only sampled the portion of the Holocene succession of particular interest to the present study.

Borehole data for this study were selected from a larger database that resides at Tulane University, based on the following criteria: (i) only boreholes from the MD were considered; (ii) a well-defined and conformable Pleistocene-Holocene transition (nearly always defined by a dark gray, immature paleosol) had to be present; and (iii) the overlying facies succession had to be at least ~2 m thick if it did not extend all the way to the land surface (thinner facies successions were only included if they showed evidence for drowning). This minimum length was chosen to ensure that at least ~400 years of record was captured. Nevertheless, we cannot rule out that lagoonal facies may occur above the section that was examined in a few of the boreholes drilled with the Geoprobe.

The spatial distribution of boreholes (Fig. 2) is associated with the paleogeography of the region during the early Holocene and covers most of the area where the Pleistocene occurs within about 15 m below present mean sea level. These are the only portions of the MD where meaningful paleo-marsh records can be obtained (i.e., those that can be tied directly to the compaction-free RSL record). The study areas are located on the flanks of a major paleovalley (40) that had been filled around the time when the first marsh facies in our record started to accumulate, reflecting lateral dispersal of sediment and initial delta formation, similar to what is seen around this time worldwide (41). Because the filled paleovalley was the nucleus for the emergence of the Holocene MD, it is unlikely that the study areas were isolated from the sediment source (i.e., the mouth of the Mississippi River). Nevertheless, since the shoreline must have migrated landward at a relatively rapid pace during the early Holocene, we cannot rule out the possibility that our study areas were sufficiently
far seaward from the river mouth to experience a temporary period of reduced sediment supply. However, it is important to stress that shoreline retreat followed by delta progradation was fundamentally driven by the rapid reduction in the rate of RSL rise (Fig. 1). In other words, any possible changes in local sediment delivery were dictated by changes in the rate of RSL rise. We also stress that the possible role of a temporary reduction in sediment supply due to shoreline retreat remains to be tested because the exact position of the shoreline of maximum transgression in this region is not well constrained.

The facies classification (table S1) builds on previous studies (42–45) with slight modifications. In several cases, the borehole descriptions lacked the detail to confidently enable facies identification, which led to a portion of the sediments being classified as undifferentiated mud or peat. The main implication of this uncertainty is that some lagoonal muds may have been missed, including in shallower cores than the age-depth range in which lagoonal muds are common (Fig. 3 and figs. S1 and S2). Since the interpretation relies heavily on the identification of these open-water facies, they were only classified as such when there was high confidence in their recognition. In other words, the interpretation was carried out with caution, and we can therefore not rule out the possibility that more extensive 14C study of this paleosol and peat from an overlying incipient and vertically accreting, organic-rich unit near the top, similar to our incipient marsh. These soils take as long as a century to evolve into fully developed, organic-rich marsh soils (48).

SUPPLEMENTARY MATERIALS

REFERENCES AND NOTES


Acknowledgments: We acknowledge the dozens of field workers who made this synthesis possible by collecting borehole data and elevation surveys during field campaigns between 1993 and 2011, and the following individuals for discussion, comments, and help: J. Day, R. Gehrels, M. Keogh, M. Kirwan, and J. Nienhuis. We are also grateful to the journal referees whose comments resulted in major improvements. We benefited from the publicly available data through the Coastwide Reference Monitoring System. This is a contribution to the PALSEA program. Funding: This work was supported by the U.S. National Science Foundation (grants OCE-0601814 and EAR-1349311) and the U.S. Department of Energy (through the National Institute for Climatic Change Research Coastal Center). Author contributions: T.E.T. conceived the study, carried out field work and a portion of the data analysis, and wrote the paper with input from all co-authors. K.L.L. carried out the majority of the data analysis. Y.-X.L. carried out field work and a portion of the data analysis. J.L.G. carried out field work and oversaw the collection of the majority of the field data. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. All the borehole data were collected by the group of the corresponding author. They reside in a digital database at Tulane University and are available upon reasonable request from the corresponding author. Surface sediment and elevation data are at https://cims.coastal.louisiana.gov/DataDownload/DataDownload.aspx>Type=soil_properties.

Submitted 18 September 2019
Accepted 10 March 2020
Published 22 May 2020
10.1126/sciadv.aaz5512

Citation: T. E. Törnqvist, K. L. Jankowski, Y.-X. Li, J. L. González, Tipping points of Mississippi Delta marshes due to accelerated sea-level rise. Sci. Adv. 6, eaaz5512 (2020).
Tipping points of Mississippi Delta marshes due to accelerated sea-level rise

Torbjörn E. Törnqvist, Krista L. Jankowski, Yong-Xiang Li and Juan L. González

Sci Adv 6 (21), eaaz5512
DOI: 10.1126/sciadv.aaz5512

ARTICLE TOOLS
http://advances.sciencemag.org/content/6/21/eaaz5512

SUPPLEMENTARY MATERIALS
http://advances.sciencemag.org/content/suppl/2020/05/18/6.21.eaaz5512.DC1

REFERENCES
This article cites 45 articles, 7 of which you can access for free
http://advances.sciencemag.org/content/6/21/eaaz5512#BIBL

PERMISSIONS
http://www.sciencemag.org/help/reprints-and-permissions