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Cultural-ecosystem resilience is vital yet under-considered in coastal restoration

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As large areas of the Mississippi River Delta (MRD) of the USA disappear into the sea, present-day communities and cultural resources are lost. While the land loss may be readily quantified, describing the impact of cultural losses is less straightforward because cultural elements are frequently less tangible and difficult to map, identify, and categorize. The elision of cultural components of landscapes and ecosystems is evident in restoration practices and policies, although numerous scholars have identified the interlinked processes of culture and ecology as critical to rebuilding healthy and resilient environments. We define and measure cultural-ecosystem resilience (CER) in the Mississippi River Delta through analyses of Indigenous oral histories, mound-building practices and settlement patterns, and the persistence and reuse of archaeological sites. CER describes a system containing resilient properties embedded in human-natural settings including river deltas that may manifest in oral cultural traditions, architecture, and the selection of habitable environments. Our interdisciplinary approach demonstrates the role of human-modified landscapes in generating resilience for past and present coastal communities and highlights the importance of consulting records of historic and modern Indigenous traditions in shaping sustainable landscape-management strategies. Results show that archaeological earthen and shell mounds made by Native American Gulf Coast and MRD communities have been persistent features that endured for centuries and are sited in regions of high multicultural value within the dynamic delta. Yet, we document the rapid 20th-century loss of mounds due to coastal erosion, industry, and other human land-use practices. Present-day and future coastal land loss endangers what remains of these keystone features and thus lowers the resilience of modern Mississippi River Delta communities.

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Introduction

The persistence of economically significant and culturally unique coastal communities threatened by environmental change (e.g., Britt et al., 2020; Couvillion et al., 2017) hinges not only on physical landscape management (e.g., Allison and Meselhe, 2010; Stive et al., 2013) but also on human endurance and adaptation. This ability of cultures to restore and reproduce in response to external stressors is known as resilience (Holling, 2001; Rodning and Mehta, 2016; Thompson et al., 2020). In resilience theory, changes are episodic with long-term and short-term cycles that impact social and cultural systems at different timescales. There are no points of stasis. Rather, complex systems are characterized by change, dynamism, adaptation, and flexibility which prevent collapse and facilitate reorganization. Resilience is relevant at the human generation, landscape management, and public-policy timescale, and it manifests on the millennial timescale in landscape-archaeological records (Faulseit, 2012; Redmond and Spencer, 2012).

Reorganization is critical to adapting to dynamic coastal environments, which are presently among the most densely inhabited and at-risk places on Earth (e.g., Giosan et al., 2014; Kulp and Strauss, 2019; Neumann et al., 2015). Archaeological sites offer the only millennial timescale records of human adaptation to environmental change in North America and therefore are of great value to inform present-day efforts to engineer sustainable coasts. For example, archaeological shells and earthen mounds along the Gulf Coast of the southeastern USA have been described as persistent places that contributed to the resilience of early Indigenous cultures (Ritchison et al., 2021; Thompson and Turck, 2009). The mounds were simultaneously foci for resilient cultural practices and institutions, like feasting, ritual renewal, and community gathering, as well as keystone features of the deltaic landscape that provided topographic relief for greater viewsheds and visibility and for enhanced biodiversity (Mehta, 2023). Within present-day Louisiana, USA, earthen and shell mounds add elevation to the low plain of the Mississippi River Delta (MRD) (e.g., Helmer et al., 2023; Mehta and Chamberlain, 2019), creating coupled cultural–natural systems that have endured the environmental perturbations of hurricanes and floods (Bregy et al., 2018) as well as shifts in the courses of rivers and streams that dictate the location and timing of formation of deltaic lobes (Fisk, 1944) and natural levees (Shen et al., 2015) and determine groundwater geochemistry (Akintomide et al., 2020). We define the dynamic in which cultural practices are intertwined and dependent on natural forces (Lepofsky et al., 2017; Liu et al., 2007) to create a system that promotes community stability as "cultural-ecosystem resilience" (CER). In addition to manifesting in the archaeological record, CER can be a key planning component for adaptation to environmental change by modern communities.

Here, we test how CER manifests in a culturally significant coastal landscape through analyses of the archaeological record and historical records of Indigenous worldviews. Our work is focused on the MRD of the USA (Fig. 1A). The MRD developed as a patchwork of lobes (or, subdeltas) formed over the past ~7000 years as avulsions of the channel network relocated the depocenter with roughly millennial-timescale periodicity (Fig. 2). These river channel dynamics generated a vast array of ecotones and geomorphic regions that shifted in time and space through the Holocene. Over the past ~100 years, little new land has been built in the MRD due to post-industrial management practices (e.g., leveeing), while old land has been lost to open water through subsidence and erosion. The unprecedented rates of 21st-century land loss in the MRD (Couvillion et al., 2017) necessitate the immediate study of archaeological sites (Britt et al., 2020) and underscore the need for inspiring approaches for modern communities to adapt to environmental change.

Our work employs three analyses centred on the Lafourche Bayhead delta region of the MRD. First, we interpret the archaeological record and cultural importance of land selected for habitation and ceremony through oral traditions of the Gulf Coast and Southeastern Indigenous peoples. We then apply a geospatial approach to quantify the relative relief of Indigenous earthen mounds of the Lafourche Bayhead delta using LiDAR data. We extend our understanding of the persistence and reuse of these culturally important sites through analyses that optimize a recently published mound-site chronology (Chamberlain et al., 2020) in combination with state-curated archives documenting historical changes and disturbances. Finally, we place our findings in the context of the changing coast to comment on management priorities to foster resilience in rapidly shrinking coastal Louisiana.

Geologic and cultural context

Geologic setting. At the mouth of the Mississippi River, where the freshwater channel meets the Gulf of Mexico, millions of tons of sediment have accumulated over the past several millennia to form the Mississippi River Delta (MRD) (Fig. 1). This delta is a component of the Gulf Coastal Plain and is a patchwork of numerous deltaic lobes (subdeltas) that formed at different times when avulsions of the distributary channels rerouted the sediment load of the river. Trunk-channel avulsions have occurred on the order of about one per thousand years over the mid to late Holocene although recent chronology demonstrates a considerable degree of spatial and temporal overlap of subdeltas (Fig. 2) (Hijma et al., 2017). A complex array of ecotomes and geomorphic regions exist within a subdelta. Natural levees accumulate through repeated episodes of river overbank flooding, and breaches in the levee known as crevasse splays deliver channelized flow and thus coarse-grained deposition to the flood basin, building up a ~1–2 km wide strip of naturally elevated land adjacent to the river channel (Shen et al., 2015). It is on this elevated land that both Indigenous archaeological sites and modern infrastructure tend to be sited in the MRD (Chamberlain et al., 2020; McIntire, 1958).

Avulsions are a key driver of a dynamic process known as the "delta cycle" (Roberts, 1997) whereby sediment deposition at the coeval river mouth converts open water to land, while at the same time, older regions of the delta built by earlier river channels naturally lose elevation and convert first to marsh and eventually to open water. In a stable or growing delta, the loss of old land is balanced by the creation of new land, meaning the delta plain as a whole maintains its area despite internal dynamics that cause regional-scale shifts in the ecology and geomorphology. The MRD has shown a positive balance over the mid to late Holocene, evidenced by the construction of a ~25,000 km^2 delta plain. This is packaged in four subdeltas referred to as the Teche, St. Bernard, Lafourche, and Modern (Balize) lobes (Figs. 1A and 2). Yet, an unprecedented net rate of loss on the order of 45 km^2/yr has been documented over the past century (Couvillion et al., 2017) suggesting that human activity and industrialization play a key role in disrupting the natural balance of the delta cycle (Chamberlain et al., 2018). The primary mechanisms to which land-area decline is attributed include enhanced rates of relative sea-level rise in part due to subsidence of the land surface (Nienhuis et al., 2017), bisection of coastal land by human-made canals that decrease marsh health and permit storm surges to penetrate and erode marshes (Morton et al., 2006), and

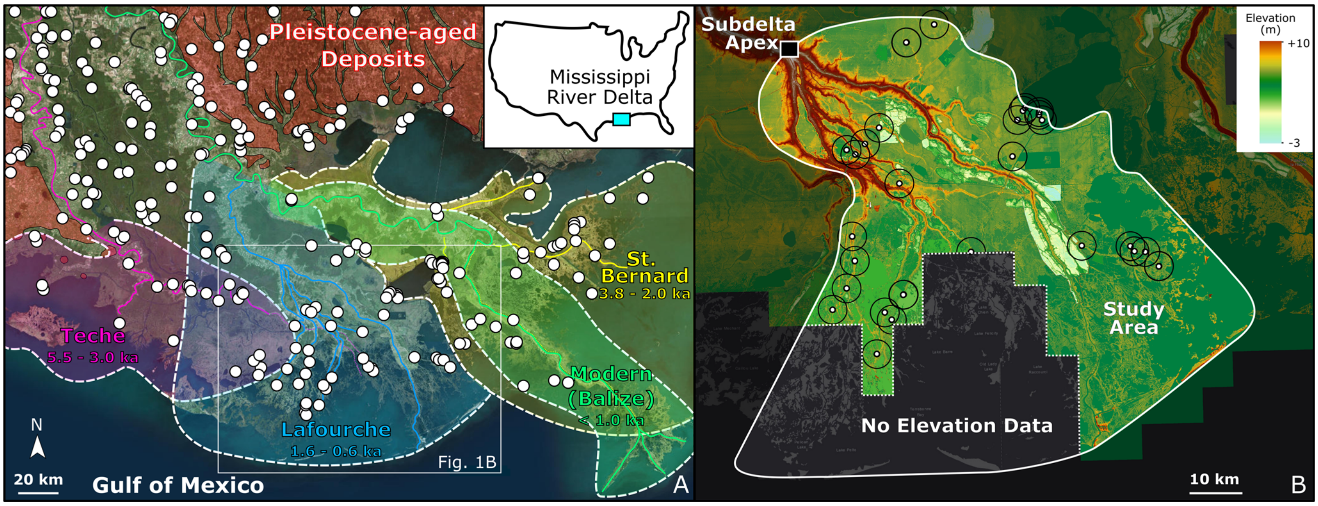


Fig. 1 Map relating geomorphology and archaeology. In **A**, the age of landforms including four Holocene-aged delta lobes and their distributary networks (white dashes, coloured fill, and coloured solid lines, respectively) and Pleistocene-aged terraces (red fill), and the location of pre-contact mound sites (white circles) in and around the Mississippi River Delta (inset), adapted from Helmer et al. (2023). In **B**, our study targets the bayhead region of the Lafourche lobe that formed through progradation into open water (Chamberlain et al., 2018), outlined in white. The land surface elevation obtained from LiDAR is shown where available. Mound sites are shown as white circles with black outlines indicating the 1 km^2 (small black outline) and 25 km^2 (large black outline) areas around the sites.

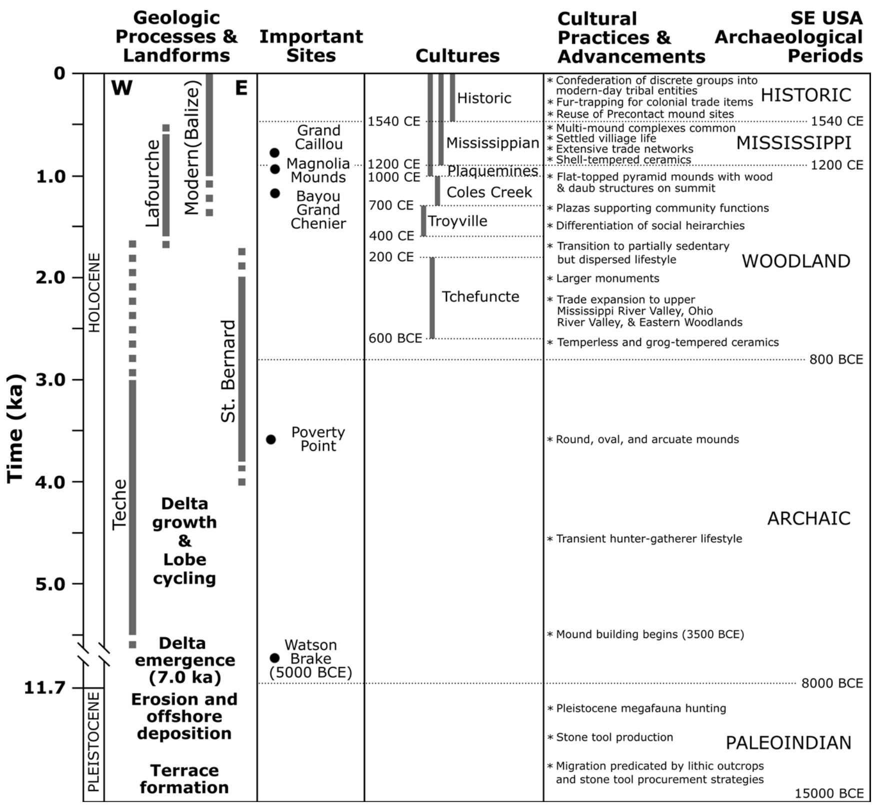


Fig. 2 Chronology of the study area. Regional timeline showing the geologic processes and landforms of the Mississippi River Delta arranged from west to east, alongside archaeological data including important sites, cultural phases, and cultural practices and advancements associated with Southeastern USA archaeological periods. Archaeologic data are synthesized from Rees (2010a).

decoupling of the river with its floodplain by artificial levees so that new land is not built to offset losses (Xu et al., 2019).

The most recently abandoned lobe of the MRD is the ~10,000 km^2 Lafourche subdelta, which was active from 1600 to 600 years ago (Shen et al., 2015; Törnqvist et al., 1996) and constructed ~6000–8000 km^2 of new land through bayhead delta progradation (Chamberlain et al., 2018) (Fig. 1B). The Lafourche bayhead delta is ideal for this study because it offers an extensive archaeological record including at least 36 pre-contact, Indigenous earthen and shell mound sites coupled with an abundance of newly published geochronologic data to support novel analyses (Chamberlain et al., 2020; Chamberlain et al., 2018; Mehta and Chamberlain, 2019).

We investigate these sites for our project because (i) As the most recently abandoned subdelta of the MRD, much of the Lafourche geomorphic and archaeological record is still in place or has been recorded by archivists. (ii) The recent application of optically stimulated luminescence (OSL) dating to sedimentary deposits of the Lafourche subdelta has yielded a high-resolution record of the timing of channel activity and formation of new land within this subdelta (Chamberlain et al., 2018) meaning the geomorphology of this region is among the best understood of the MRD and of megadeltas in general. (iii) Recent innovations have provided new chronologic constraints for Lafourche bayhead delta mound sites constructed before European contact (Chamberlain et al., 2020). In other words, there is a wealth of geomorphic and archaeological data in the bayhead region of the Lafourche subdelta on which we build our analyses.

Cultural setting. The earliest monuments in North America were built by hunter-gatherers in what is now Louisiana, the Lower Mississippi Valley, and in parts of Florida, making the Southeastern United States a critically important area for studying the early development of social and political complexity in the Americas. Nowhere is this more evident than at the recently categorized UNESCO World Heritage site of Poverty Point (Fig. 2), located today in Epps, Louisiana (Gibson, 2007; Greenlee, 2015). The Poverty Point site, constructed between 1600 and 700 BCE, has evidence of one large 30-m-tall mound, several small mounds, and six arcuate-shaped rings that span 1.2 km. It is not the earliest monumental site in the region—the honour belonging to the Watson Brake site, a circular ring of earthen mounds dating to around 5000 BCE (Saunders et al., 2005)—but Poverty Point is certainly one of the most impressive. Over a span of 7000 years, monument construction in the form of earthen and shell mounds remained a salient component of lifeways in the Lower Mississippi Valley and coastal Louisiana (Fig. 1A).

By the time agriculture and the monument-building tradition gained prominence in the Central Mississippi Valley, around CE 1000, Coles Creek and Plaquemine cultures were still engaged in hunter–gatherer–fisher lifeways along the Gulf Coast and deltaic lobes of the Mississippi River (Rees, 2010a). Plaquemine cultures are most clearly identified by earthen mounds, grog-tempered ceramics, bone tools, and occasional stemmed lithic projectile points (Brain, 1989; Kidder, 2007; Neuman, 1984; Rees, 2010a). Unlike Mississippian cultures to the north at Cahokia, Moundville, and elsewhere (Knight and Steponaitis, 1998; Pauketat, 2004), scholars suggest Plaquemine societies may not have exhibited strong social hierarchies and were largely independent and insular without extensive trading networks, and that by the beginning of the historic period, Mississippians and Plaquemine people had sufficiently mixed and hybridized (Rees, 2010a).

Coles Creek, Plaquemine, and Mississippian cultural history are the most relevant for our work in the Lafourche subdelta, considering its age. Figure 2 provides an overview of the cultures, archaeological periods and cultural practices, and important mound sites alongside the geologic history of the MRD, including those most relevant to our study area. In general, peoples of the Mississippi Delta from 400 to 1400 CE comprised hunter–fisher–gatherer societies that transitioned toward increasingly sedentary, village-focused lifestyles with time. They produced ceramics, engaged in increasingly complex trade networks, and constructed large, monumental complexes characterized by shell middens and flat-topped pyramid-shaped earthen mounds arranged around plazas in which ritual and ceremonial activities took place. Coles Creek (700–1000 CE) and Plaquemine societies (>1000 CE) are differentiated based on variations in ceramic manufacturing techniques, differences in mound utilization, and a shift to more complex forms of ranking and social organization.

Any sites older than Coles Creek cultures, like Tchefuncte culture, along the Lafourche delta are likely buried and destroyed by the formation of the deltaic lobe itself. Tchefuncte culture is dated from 600 BCE to CE 200 (Kidder et al., 2010; McIntire, 1954, pp. 72–74) and it predates an expansion of Coles Creek cultures around the middle of the first millennium CE (Roe and Schilling, 2010). Coles Creek cultures expanded northwards towards Natchez, Mississippi (Kassabaum, 2019, 2021), and their sites can be found across the MRD (Roe and Schilling, 2010; Schilling, 2004). Both Tchefuncte and Coles Creek cultures were hunter–fisher–gatherer societies who made ceramics and lived regionally delimited lives, not engaging in long-distance trade and exchange, however, Coles Creek cultures erected and lived on earthen mound complexes with far greater frequency than Tchefuncte cultures. Notable Coles Creek complexes in the MRD include the Bayou Grand Cheniere site (Schilling, 2004), which is comprised of eleven mounds built around an oval plaza. Platform mounds are found at the northern and southern ends of the site, in between which are smaller conical mounds. Later, Plaquemine cultures, which are thought to develop from Coles Creek society, and Mississippian cultures, thought to represent culture complexes from further upriver, come to settle and occupy the entire expanse of the MRD and coastal Louisiana.

Plaquemine cultures also constructed earthen and shell mound complexes after CE 1200 and until European contact; notable sites include Grand Caillou (Mehta and Chamberlain, 2019), Adams Bay (Mehta et al., 2020), and Buras (Rees, 2010b) These sites were single mound sites and mound complexes, with platform mounds arranged around plazas in which ritual and ceremonial activities took place. Coles Creek and Plaquemine societies are differentiated based upon variations in ceramic manufacturing techniques, differences in mound/monument utilization, and a shift to more complex forms of ranking and social organization. One of the most notable sites in the region is the Magnolia Mounds complex, comprised of eleven earthen mounds arranged around an oval plaza, and located just off the eastern edge of Lake Borgne (Kidder, 2004; Watt et al., 2020). The landform and earthen mounds were first constructed in the middle of the first millennium CE by Marksville cultures (McIntire, 1954, pp. 79–80) and the site was later reoccupied and terraformed into a monumental complex by Coles Creek and Plaquemine peoples. Other Plaquemine sites can be found on the western and southern margins of the MRD, including in our Lafourche study area.

Detailed excavations of sites in the lowermost portions of the late Holocene MRD including the Lafourche subdelta are rare. Mehta and Chamberlain (2019) investigated the Grand Caillou mound complex of the Lafourche Bayhead delta and linked this site to the Plaquemines culture of the Mississippi period based on recovered ceramics typology. Radiocarbon dating of organic material recovered within the mound deposits and of an underlying forest floor peat placed the timing of mound construction and use at CE 1200–1400 (Mehta and Chamberlain, 2019). Landscape analyses and OSL dating of natural sedimentary deposits underlying the primary Grand Caillou mound and another mound at the nearby Ellesly site, also within the Lafourche bayhead delta, showed that both sites were situated on naturally high elevation distributary channels and built a few hundred years after the land emerged from open water (Chamberlain et al., 2020). Using this relationship of mound construction and land emergence, Chamberlain et al. (2020) estimated the maximum age and likely age of 36 pre-contact Indigenous mound sites in the Lafourche Bayhead delta, many of which had not been dated by other means and were disturbed or destroyed, rendering direct chronology impossible.

Settlement pattern studies indicate that complex societies inhabited the Mississippi River Delta region for thousands of years (Kniffen, 1936; McIntire, 1958) and mound construction has been related to the timing of natural land-building deltaic processes (Chamberlain et al., 2020). A timeline summarizing the geologic and archaeologic developments of the MRD is offered in Fig. 2. While both aspects of the region have been widely studied, research linking geology and cultural prehistory is rare. Anthropologists have focused on social hierarchies, site-size relationships, ceramic chronologies, and cultural models of these coastal peoples (Davis, 1984; Giardino, 1984; Kniffen, 1936), yet few have directly emphasized issues related to sustainability, vulnerability, resilience, how these processes were integrated into Indigenous lifeways and their implications for the future. Our work fills this research void by identifying the coupled natural and cultural processes linked to the pre-contact Indigenous inhabitants of the dynamic delta ecosystem and landscape.

Methods

We used three analyses to investigate how CER is embedded within the monumental landscapes of the Mississippi River Delta: (i) evaluation of ethnohistoric and historic documents describing Indigenous oral traditions from the Gulf Coast, (ii) a quantitative analysis of the elevation and relief of pre-contact mound sites relative to the surrounding delta plain, and (iii) a quantitative analysis of the persistence and reuse of these archaeological sites, placed in the context of post-industrial human modifications of the landscape and our changing coast.

Oral traditions. No single model or explanation can be proposed for why monumentality is practiced by cultures across the entirety of the globe; here we offer a collection of stories once told by Indigenous peoples of the Southeastern USA. Oral traditions were compiled from published primary sources using several different criteria: (i) belonging to Indigenous Gulf Coast or Southeastern communities, (ii) concerning ethnogenesis, world formation, and mounds, and (iii) originally recorded by an anthropologist or by an Indigenous community member or from someone of Indigenous descent. Excerpts are provided in the Supplementary Information.

Relative relief. Site coordinates were imported and mapped using ArcGIS and superimposed over publicly available pre-processed light detection and ranging (LiDAR) data collected by the State of Louisiana in 2000. We observed that processing of the LiDAR clipped (i.e., artificially removed or minimized) some mounds that were likely interpreted as vegetation. To accommodate this, we grouped the sites into three categories based on their preservation and appearance in LiDAR and Google Earth satellite imagery: (i) sites visible in both satellite and LiDAR imagery, (ii) sites visible in satellite but not LiDAR imagery indicating the mound features were clipped during LiDAR processing, and (iii) sites not visible with either type of imagery suggesting the destruction of the mounds (Fig. 3). For sites in the first group, LiDAR elevations were recorded at the mound summit and on the landscape immediately adjacent to the mound. For sites in the second and third groups, landform elevations were measured at the mound coordinates obtained from State of Louisiana site record forms. We checked the LiDAR-derived mound elevations against the relief of mounds recorded in the Site Record Forms, when available.

Seven of the 36 mound sites identified by Chamberlain et al. (2020) were rejected from analysis because they were outside the area of LiDAR coverage. Two sites featured two distinct mounds, giving a total of 31 data points. All elevations are recorded as present-day values in meters relative to NAVD 88. Notably, these represent minimum elevations due to land-surface subsidence since landscape deposition and mound construction. Shallow subsidence in our study area is greatest at the highest elevation places (i.e., the banks of distributary channels, particularly at inland locations) because the thick package of overbank deposits that generates relief also causes load-driven compaction of underlying strata (Chamberlain et al., 2021). Yet, the average elevation of the Lafourche Bayhead delta is likely a maximum estimation because much of the lowest-lying land has already converted to open water for which LiDAR data were not available (see Fig. 1B). Combined, this means our assessment is conservative because archaeological site elevations are minimum estimates and the average land elevation to which they are compared is a maximum estimate. We identify an archaeological site as possessing the elevation characteristic of CER if the site-landform elevation is greater than the average elevation of the surrounding landscape, defined here as the 25 km^2 daily foot-travel distance.

Persistence age. The chronology of sites in our study area was refined by Chamberlain et al. (2020), who offered a *terminus post quem* (maximum time of construction) and likely age based on OSL dating, radiocarbon dating, and landscape reconstructions detailed in that work. We analysed the Site Record Forms of 36 pre-contact Indigenous mound sites identified by Chamberlain et al. (2020) to determine (i) the time of first recorded disturbance of the site, (ii) the time of the destruction of the site (if applicable), and (iii) the agent(s) causing disturbance and destruction. See Chamberlain et al. (2020) for a comprehensive description of Site Record Forms. Three of the 36 sites were excluded from the analysis due to insufficient data. Many entries to the Site Record Forms of Louisiana were made in the 1950s and again in the 1970s and 1980s, but records for the 21st century are sparse. To evaluate the present-day condition, we conducted site visits when possible and used Google Earth imagery in which sites typically manifest as circular oak-inhabited “islands”. We calculated the maximum persistence age of the site as the date of destruction (or, present-day if the site has not been destroyed) minus the *terminus post-quem* age (Chamberlain et al., 2020), and we calculated the minimum persistence age as the date of last recording of the site in Site Record Forms minus the likely age of construction (Chamberlain et al., 2020).

Results and discussion

Our analyses of oral traditions, relative relief, and persistence age yield results that describe societal, geographical, and chronological aspects of CER within archaeological sites of the Mississippi Delta. Broadly, western science as a discipline has disregarded other world views. In recognition that oft-overlooked perspectives including those of Indigenous peoples are an integral part of the fabric of coupled human-natural systems, we begin with our findings on the meaning of place drawn from oral traditions of Gulf Coast peoples.

Oral traditions. The natural phenomenon of land creation is recorded and performed by mythical figures in Indigenous oral traditions and stories, many of which are still told by living descendant communities (Lauer, 2012). Our analysis shows that the building of earthen and shell mounds served to encode meaning into the landscape. Iconographic designs on Indigenous North American ceramics evoke a tripartite universe composed of a sky vault, middle world, and below world (Lambert, 2018). Earthen and shell mounds are an axis mundi and, like clay pots, their composition entails clay, silt, and sand elements of the lower

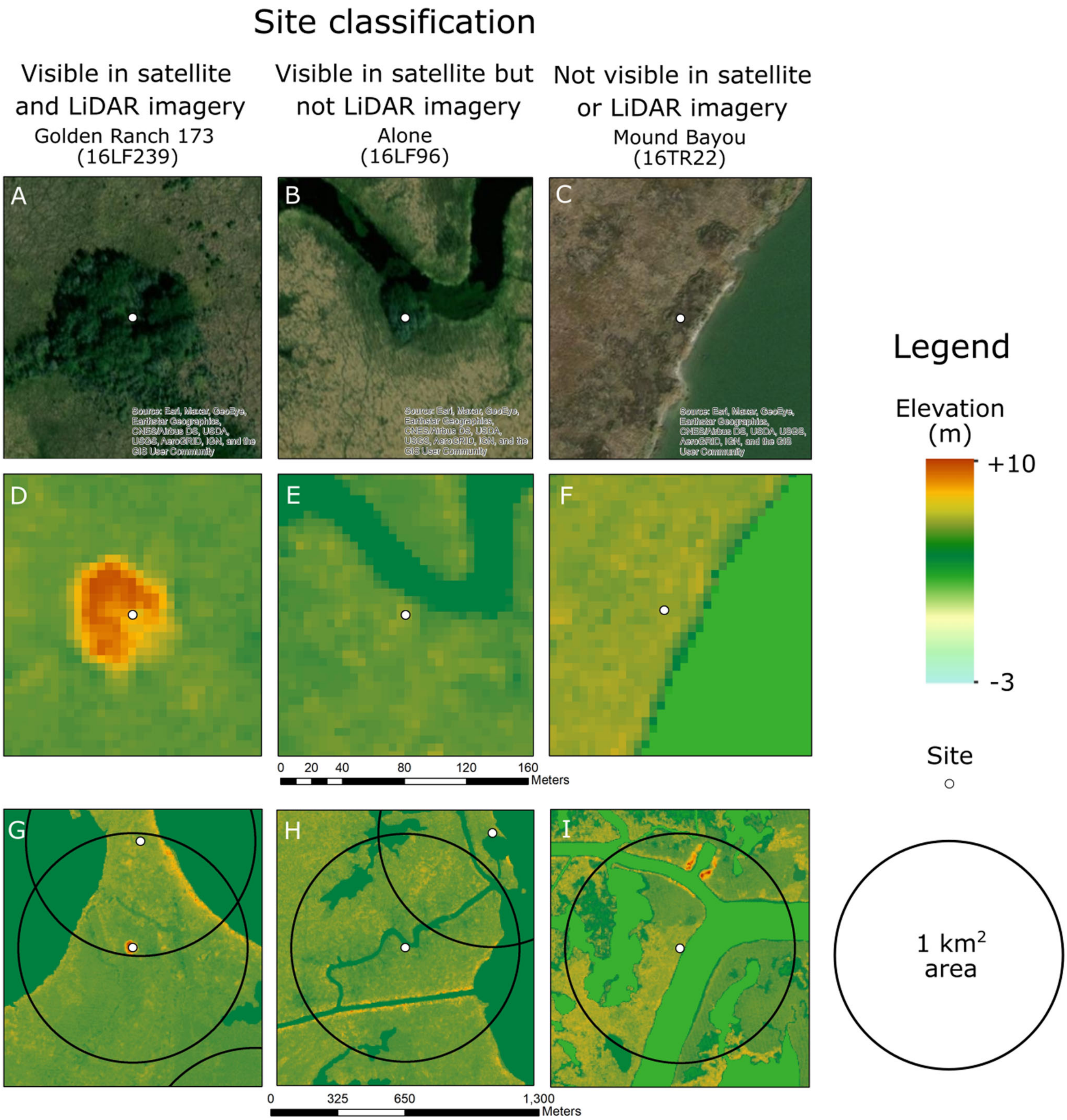
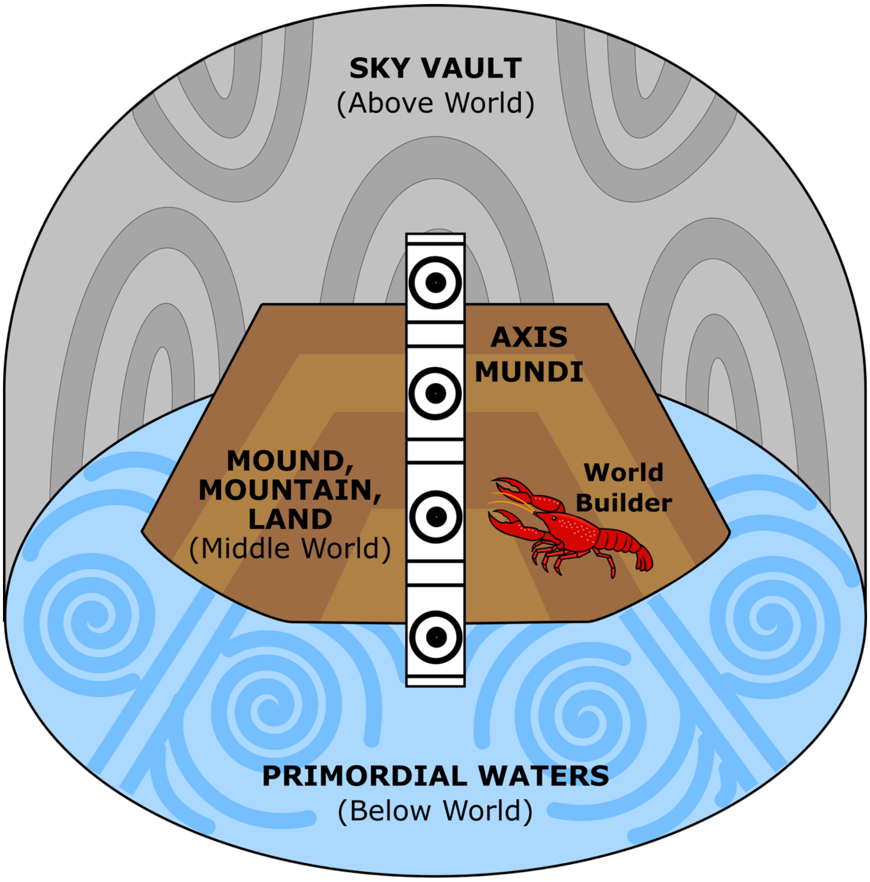


Fig. 3 Site classifications and spatial boundaries used in the relative-relief analysis. Three site types are identified and an example of each is provided: those visible in both satellite and LiDAR imagery (**A**, **D**, **G**), those visible in satellite but not LiDAR imagery (**B**, **E**, **H**), and those not visible with either type of imagery (**C**, **F**, **I**). For each site type example, the zoomed-in Google Earth satellite (**A**–**C**) and LiDAR (**D**–**F**) imagery are shown. The zoomed-out position on the landscape and 1 km^2 area surrounding the sites, from which average land-surface elevations were obtained, are demonstrated (**G**–**I**).

world (Fig. 4). In this way, mounds may connect individuals to the upper world through elevation and topography and are thought to be linked to the sky vault at their four corners (Kidder, 2013; Knight, 1986). Consequently, we can employ oral traditions to link the building of mounds and their use to processes of world-building, land formation, and the engineering of durable and resilient landscapes in dynamic, deltaic environments.

Along the Gulf Coast and among the many different Indigenous communities of southeastern North America, oral traditions reveal that a mythical figure called Earth Diver formed the land from which Native nations originated (Grantham, 2002; Judson, 1914; Swanton, 1995). These histories revolve around topics of creation, emergence, ethnic identity, and group cohesion. In many cases, the stories compare natural land-building processes to the actions of real and mythological animals (Rodning and Mehta, 2016) (Fig. 4). For example, an oral history of the Chitimacha, a Gulf Coast Indigenous community, depicts a version of the Earth-Diver mythology in which a crawfish descended into primordial waters to obtain land for Chitimacha villages (Judson, 1914; Rodning and Mehta, 2016). Two salient points emerge here: (i) a crawfish plays an important role in forming land, and (ii) mounds are camping places of spirits.



Mythic Elements

Primordial State	*Earth(works)*	*World Builder*	**Tribe**	**Reference**
Earth under water	Mound	Crawfish	Chitimacha	Judson (1914)
Clay genesis		Frog		Swanton (1929)
Cave		Crawfish	Alabama	Grantham (2002)
	Mountain		Tunica	Haas (1950)
	Earth Island		Cherokee	Mooney (1995)
Water			Apalachicola	Grantham (2002)
Wet ground		Earth diver	Creek	Grantham (2002)
Water	Mound	Earth diver (crawfish)	Yuchi	Grantham (2002)

Fig. 4 Schematic illustration showing the ordering of the cosmos as interpreted from mythemic analysis of Southeastern Native American stories concerning world-building. Numerous stories about how the world was made were consulted and synthesized into this image and table, and the realms are enhanced with iconographic textures drawn from ceramics motifs (see also Lambert, 2018 and Stauffer et al. 2022 for additional discussions on the archaeological interpretation of cosmology).

Another story describes a bird transporting a single grain of sand in its beak and depositing it over floodwaters to make land (Judson, 1914). Both evoke the ways in which sediment is carried and deposited by rivers and coastal floods to build deltaic land, and numerous variations of Earth-Diver and emergence themes are found in the oral histories of Southeastern Indigenous peoples (Haas, 1950; Mooney, 1995) (Fig. 4). These are but two of many examples in which Earth Diver plays a critical role in Native cosmologies and narratives of ethnogenesis.

Building with earth/mud/sediment is fundamental in these mythologies, and this practice is especially salient in a region like the MRD that is so clearly defined by the river and coastal flooding and a delicate balance of sediment deposition and erosion that dictates the local ecology and suitability of land for humans (Chamberlain et al., 2020; Kidder, 2000). Our analysis demonstrates the value of mound construction as a means of coupling natural landscape and human-spiritual elements to create culturally important, permanent places. In other words, earthen mound construction was an Indigenous means of enacting CER because it enhanced cultural memory, sustainability, and the long-term meaningfulness of the landscape.

Relative relief. It is widely recognized that humans have a preference to occupy high-elevation land, especially in coastal plains and deltas (Holz, 1969; Politis et al., 2011; Stanley and Chen, 1996). This phenomenon is observed in both pre-contact and present-day societies yet research on the elevation component of landscape desirability remains highly qualitative. While it is commonplace to describe the geomorphic attributes of cultural and archaeological sites (for example on a beach ridge, natural levee, terrace, or bluff), the numerical relief provided by such high-elevation natural features is typically vague. A lack of

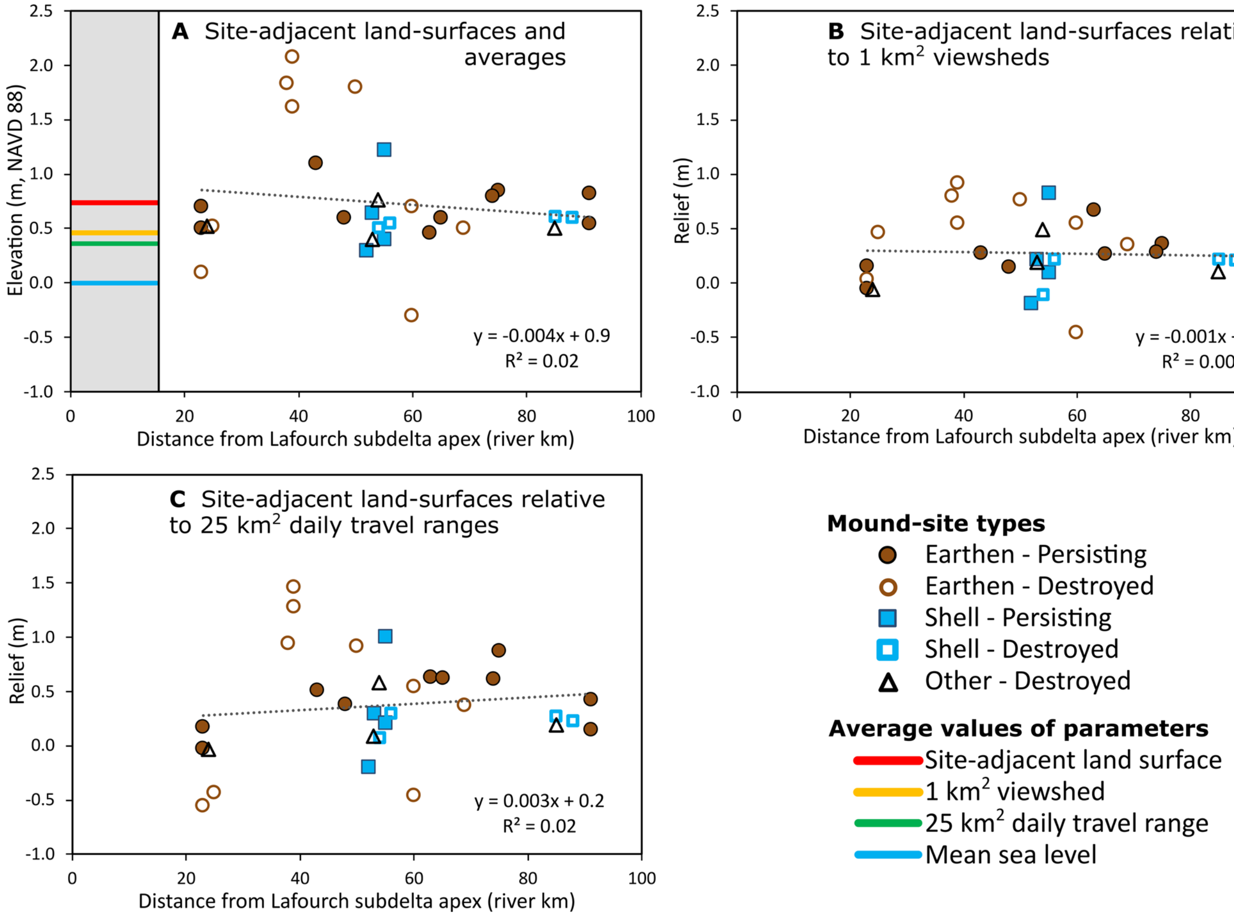


Fig. 5 Regional elevation results. Elevation characteristics of the study area and mound sites including. **A** Site-adjacent land-surface elevations for individual sites versus distance from the Lafourche subdelta apex, and average elevations for other parameters, **B** the relative relief of mound sites compared to their 1 km^2 viewsheds, and **C** the relative relief of mound sites compared to their 25 km^2 daily travel ranges. Sites are grouped by construction material and present-day condition. Supporting data are found in Table S1, and mean sea level data are from NOAA tide gauges (tidesandcurrents.noaa.gov; Table S2).

quantitative geomorphic data has hindered the interpretation of the geomorphic parameters of archaeological sites in the context of resilience.

Through LiDAR analyses, we find that the average present-day elevation of the natural land surface adjacent to Indigenous mound sites is 0.74 ± 0.09 m, the average elevation of the 1 km^2 perceived human viewshed (Hally, 1993) of the mounds is 0.46 ± 0.06 m, and the average 25 km^2 daily travel range (Hally, 1993) around the mounds is 0.36 ± 0.05 m (Fig. 5A). The average elevation of the present-day Lafourche bayhead delta for which LiDAR is available is 0.45 m. In the low-lying MRD where elevation is a proxy for ecology and environment, the similarity of viewshed, travel range, and average bayhead delta elevations all indicate that the location of sites availed pre-contact Indigenous communities to a variety of ecotones and their resources. These likely ranged from fish- and game-rich interdistributary basins to higher-elevation vegetated natural levees. Said differently, all the diverse resources of the delta were within one day's travel from pre-contact Indigenous cultural centres.

The relative relief of mound sites compared to both the travel range (Fig. 5B) and viewshed (Fig. 5C) of the sites are fairly constant across the bayhead delta and for earthen vs. shell mounds. On average, mounds are sited on land that is presently 0.3 ± 0.1 m above their 1 km^2 viewshed and 0.4 ± 0.1 m above their 25 km^2 daily travel range (Table S1). While this relief may seem small, it is significant in a microtidal landscape like the MRD where the mean tidal range is ~0.4 m (Table S2). Here, a natural elevation advantage of only a few decimetres can make the difference between diurnal inundation, monthly inundation, or largely dry and habitable conditions. This degree of elevation would not have likely offered significant protection from inundation during episodic, high-magnitude flooding events (i.e., tropical storms and hurricanes). Rather, the position of sites inland relative to the coeval shoreline would have offered some buffer against storm surges, as mentioned by Chamberlain et al. (2020). Assuming a shoreline progradation rate of 100–150 m/yr (Chamberlain et al., 2018) and site construction 200–400 years after land emergence at a site (Chamberlain et al., 2020), we estimate that sites were built 20–60 km inland of the coeval shoreline. Nonetheless, coastal and meteoric flooding likely posed challenges for pre-contact Indigenous communities as they do for southern Louisiana communities today.

Eighty-one percent of sites are located on land elevated about the surrounding broader landscape, suggesting that the vast majority of selected sites naturally possessed a landscape quality of CER. The building of monuments on high-elevation landforms enhanced the inherent value of the natural levees, provided additional benefits such as protection from flooding, relief from flying insects, extended visibility, as well as fostered biodiversity (Balée and Erickson, 2006; Mehta et al., 2020). Similar benefits are gained from sitting relatively inland on the coeval shoreline. The average mound-summit LiDAR elevation is 1.95 ± 0.14 m and truthing to archival documents suggests this is an underestimate due to LiDAR clipping, as many mounds were recorded to reach much higher (up to 7 m) above the natural land surface.

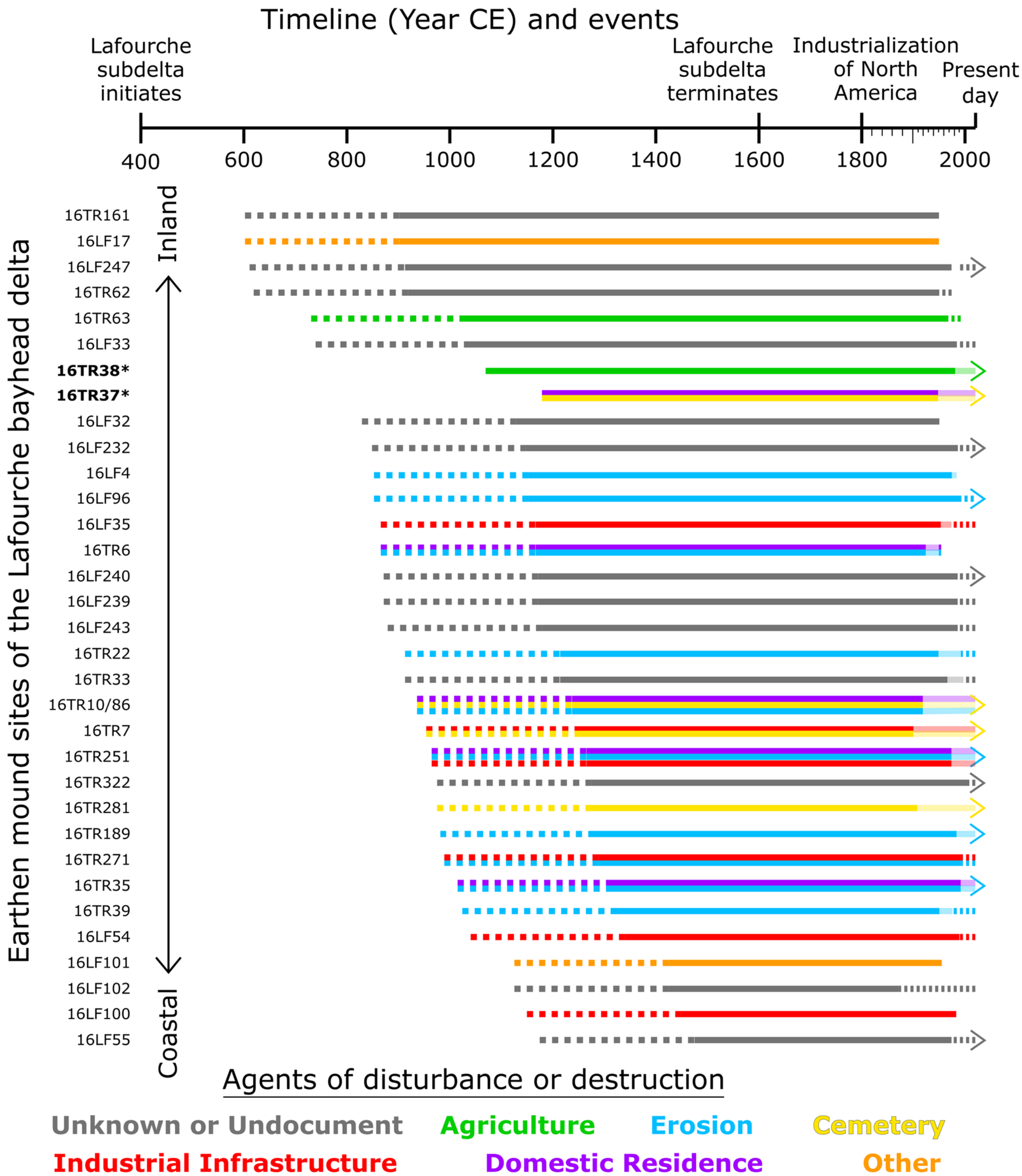


Fig. 6 Timeline showing the persistence of pre-contact earthen mound sites of the Lafourche Bayhead delta in the context of the region's geologic and human history. The coarse dashes to the left indicate uncertainty in the timing of site construction (Chamberlain et al. 2020), and fine dashes to the right indicate uncertainty in the condition of the site following the last entry in its Site Record form. The solid line shows the interval of confidence in the site's existence, and the faded line indicates the time since the first recorded disturbance of the site. Arrows indicate the persistence of sites verified by Google Earth and LiDAR analyses or site visits. The agents of disturbance are colour coded as indicated by the legend; some sites have been disturbed by more than one agent. Sites are ordered geographically from inland (upper) to coastal (lower) and the site file numbers of the previously studied Ellesly and Grand Caillou sites are indicated in bold text.

Regardless, mound building presents a dramatic multi-meter enhancement of the naturally low and flat (less than 1 m in most places) delta. The natural elevation of selected locations and enhancement of this elevation through mound construction generated a physical property of resilience for coupled human–natural communities. Surprisingly, we see no relationship between mound-site landform elevation or relief and preservation status, nor between preservation status and distance to the coast (Fig. 5). This suggests that factors other than simply coastal erosion and submergence are at play in mound destruction, a topic that is explored through our persistence age analysis.

Persistence age. Plotting the persistence ages of the archaeological sites (that is, the time elapsed between mound construction and destruction or present-day) and their agents of destruction or disturbance reveals several insights into these valuable features (Fig. 6). All archaeological sites studied herein were documented to persist at least five centuries, until at least the late 19th century and typically into the latter half of the 20th century at which point disturbance became prevalent. This corresponds with a period of enhanced industrial activity, particularly within oil and gas (Morton et al. 2006), although our analysis shows numerous agents acted in disturbance and destruction. It is possible that some sites were destroyed prior to 20th-century recording efforts and are therefore not represented in this study. The data capture the rapid loss of sites from the mid-20th century onward. Nine sites (27%) were recorded as destroyed, and we were unable to verify the present-day existence of an additional 8 (24%) sites with Google Earth, LiDAR, or archival survey reports. Only 16 sites (48%) were verified to still exist in some condition.

The same agents to which the modern MRD land-loss crisis is attributed are among those which have driven the loss of archaeological sites. We identify seven classes of destructive and disruptive agents: erosion, industrial infrastructure, agriculture, intrusive historic cemeteries, domestic residences, other disturbances (shell mining and road construction), and unknown or not recorded. Agriculture was found to be an important mechanism of loss at inland sites. Industrial infrastructure (typically oil and gas fields and canals) and erosion (along the banks of artificial canals or natural levees) were dominant in most coastward regions. It should be noted that erosion and subsidence are concomitant; we do not differentiate between these processes in our analysis and we recognize that subsidence affects much of the lower MRD plain and enhances the vulnerability of sites to erosion.

Our investigation revealed that many sites have cultural components that postdate the primary occupation by Indigenous people, including repurposing as historic cemeteries, plantation estates, fishing camps, and a school and brick factory. Historic cemeteries are the earliest agent of disturbance documented by our analysis, yet, all sites with intrusive burials persist today. The reuse of Indigenous pre-contact mounds as historic cemeteries is evidence that high societal value is placed on these naturally and artificially elevated features across generations and cultures—this value has likely contributed to their protection from modern destructive agents (e.g., industrial infrastructure) and thus supported their persistence as elements of the landscape that enhance resilience. Cemeteries across many cultures are incredibly important components of the landscape, marked in many places by fencing, tombstones, religious iconography, and spatial delimitation. In the US, cemeteries are afforded numerous protections under federal, state, and local/municipal codes, frequently categorized as sacred grounds. The importance of cemeteries is inscribed in the long Western tradition of marking graves with tombstones and other elaborate forms of recognition. This importance carries into the early colonial and historic cemeteries that were emplaced into Indigenous mounds—in many low-lying parts of the coastal zone, bodies must be placed in vaults above ground and not buried, due to the shallow water table. It was only in the Native mounds that early colonist could bury their dead, and through this act of remembrance, they created new monuments that facilitated the persistence of earlier Indigenous mounds.

Finally, we identify knowledge gaps within our analysis, specifically, the paucity of data describing the 21st-century condition of sites. This underscores the lack of financial support that has been available for the documentation of archaeological sites in Louisiana and, more broadly, the marginalization of Native perspectives within the historical records of the USA.

Conclusions

Cultural-ecosystem resilience describes the stabilizing dynamic between cultural practices and the physical environment in coupled human–natural systems; defining this concept enables evaluation of the role that culture plays in landscape modification and sustainability. Our research provides evidence of CER in the relationships between topography, mound building, and published Indigenous oral histories. We demonstrate that the construction of earthen mounds served as a means of enacting mythology and creating persistent places of spiritual significance to Indigenous peoples in which natural and cultural attributes were blended while serving the practical purpose of inland, elevated platforms that offered protection from flooding and longer-term changes to environment and ecology. Siting on natural levees enhanced the elevation attribute of the locations while offering proximal access to a wide range of deltaic resources including those found at lower elevations. The multi-century persistence and significant reuse of these sites indicate their high societal value transcends time and culture—natural levees remain of paramount importance in coastal Louisiana today and mounds have been repurposed in historic and modern times. It has been further demonstrated elsewhere (e.g., Kidder, 2000) that the relief offered by mounds creates ecological islands that foster biodiversity in the MRD. Taken as a whole, the time-tested cultural and physical value testifies to the importance of mounds as a vessel for resilience and supports the interpretation of these features as 'keystone landforms'. This means that Indigenous pre-contact mounds are important to the stability and function of various, interlinked systems in the MRD and potentially in other river and coastal landscapes.

Action is urgently needed to protect pre-contact Native American archaeological sites in southern Louisiana (Britt et al., 2020) because these sites and the landforms that host them have experienced high rates of disturbance and loss over recent decades. Coastal restoration initiatives on the order of $50 billion (CPRA, 2017) are planned to mitigate land loss and guard the future of industry and communities in present-day coastal Louisiana. Yet, few resources have been dedicated specifically to the protection of archaeological sites in Louisiana (Helmer et al., 2023). We argue that management plans that omit the role of ancient and modern Indigenous communities in shaping contemporary landscapes misidentify restoration points and insufficiently model the mechanisms of environmental change. Geoarchaeological archives offer the only millennial-scale records for human adaptation to environmental change in North America and, as we demonstrate, are an important parameter of resilience that is critical to coastal sustainability. For these reasons, we propose that government agencies, both in Louisiana and elsewhere, should explicitly incorporate archaeological sites as a keystone cultural, ecological, and physical component of the landscape that must be considered in future environmental management and mitigation plans.

Data availability

All analytical data supporting this manuscript are provided in the Supplementary Information, Tables S1 and S2. The site record forms used herein are curated by the Louisiana Division of Archaeology and may be obtained by request (https://www.crt.state.la.us/cultural-development/archaeology/).

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Author contributions

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