Estuaries and Coasts
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MANAGEMENT APPLICATIONS

Transformative Impacts of Sea-Level Rise, Storm Surge, and Wetland Migration on Intertidal Native Shell-Bearing Sites in Florida's Largest Open-Water Estuary, Tampa Bay, Florida, USA

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Abstract
Although shell middens and mounds often occupy the same intertidal spaces as coastal wetlands, biophysical interactions between these cultural features and wetlands are under-investigated. To this end, our geoarchaeological and zooarchaeological research at three coastal archaeological sites within the Tampa Bay Estuary, USA, sought to understand the interactions between shell-bearing sites, sea-level rise, storms, and migrating wetland habitats. Percussion core transects document the accretion of mangrove peat atop intact shell midden, illustrating the ability of mangrove forests to encroach shell midden and preserve cultural material below. Landward wetland deposits are thicker and muddier than those along the seaward margin of the sites, suggesting that shell-bearing sites attenuate wave energy much like other shoreline stabilization structures. Differences in sedimentology, stratigraphy, and invertebrate species compositions highlight the variability in storm impacts between sites. Storm-driven depositional events are identified by medium-to-fine sand beds with high densities of fragmented shell and small intertidal zone snails. Geospatial analyses indicate that wetland encroachment is already occurring at 247 archaeological sites within the Tampa Bay Estuary. Approximately 100 additional archaeological sites currently located in upland habitats may provide topographic relief for migrating coastal wetlands in the future. We contend that shell middens and mounds constructed by Indigenous peoples are important components within estuarine mosaics, as they have been for millennia. We advocate for further collaboration between archaeologists and estuary managers and the inclusion of descendant communities to co-manage the future of their past.

Keywords Geoarchaeology · Mangrove encroachment · Intertidal transformations · Tampa Bay Estuary · Storm taphonomy

Introduction

The consequences of climate change on coastal communities and habitats are numerous and imminent (Dolan and Walker 2003; Gillanders et al. 2011; Robins et al. 2016). Accelerated sea-level rise, ocean acidification, and increased frequency and intensity of storms are only a few of the challenges associated with increases in greenhouse gases, and these shifting variables often amplify existing stressors in estuaries (Scavia et al. 2002). While many coastal communities are experiencing the impacts of climate change, so too is the archaeological record of coastal areas around the world (Erlandson 2008; Gregory et al. 2022; Rowland 1992). Scientists are rapidly assessing the ongoing and projected impacts of climate change on cultural and natural resources along coastlines (e.g., Anderson et al. 2017; Cochran et al. 2023; Colombano et al. 2021; Gabler et al. 2017; Osland et al. 2022; Parkinson et al. 2023; Reeder-Myers 2015). However, in many cases, these contemporary and archaeological resources occupy the same intertidal spaces and persistently interact with one another.

There remains a lacuna of research that considers biophysical interactions between contemporary estuarine wetland habitats and coastal shell-bearing sites constructed by Indigenous peoples (e.g., shell middens and shell mounds). The paucity of integrated archaeological and ecological research dedicated to the present and future roles of shell-bearing sites in estuaries is surprising given the fact that

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these sites have long histories of interaction with tidal environments and coastal processes (see Jackson et al. 2023a, b; Parkinson 2023). The earliest archaeological evidence of shellfishing dates to circa 164,000 years ago on the southern coast of South Africa, and shellfishing and the adaptation to dynamic coastal environments have been hypothesized as a vital factor in the dispersal of anatomically modern humans out of Africa (Marean et al. 2007; Walter et al. 2000). As humans migrated to new coastal areas and shellfishing became more ubiquitous, the deposition of food remains, alongside other occupational debris, left remarkably durable sedimentary evidence of human land use. Shell-bearing sites are found in coastal areas worldwide; some of the most substantial deposits are documented in Brazil, Japan, California, and Florida (Erlandson 2013; Fish et al. 2013; Habu et al. 2011; Luby et al. 2006; Thompson et al. 2016). Archaeologists have described great diversity in the shape, size, and formation processes of shell-bearing sites and features (e.g., middens, mounds, shellworks, ridges, rings, platforms) (Marquardt 2010; Saunders and Russo 2011; Schwadron 2017). Given that all these archaeological site types interact with sea-level rise, storms, and coastal wetlands, and to avoid any functional connotations, we use the term *shell-bearing sites* to collectively refer to all coastal archaeological sites with cultural mollusk shell matrices. Shell-bearing sites contain deep-time records of human-environmental relationships, paleoclimatic and paleoecological archives, and cultural significance that extends into the present (Erlandson and Braje 2013).

Coastal wetlands worldwide are being forced to adapt to rising seas and saltwater intrusion (Borchert et al. 2018; Enwright et al. 2016). Urbanized shorelines constrain their landward migration and lead to wetland loss—a process known as coastal squeeze. Osland and colleagues (2022:1) observe that sea-level rise research has disproportionately concentrated on the erosion and submergence of seaward wetlands rather than quantifying the “transformative impacts” on landward wetland mosaics and coastal uplands—a pattern that has likely led to the underestimation of projected wetland losses due to sea-level rise. Our study documents the estuarine transgression of a coastal upland habitat that has been widely overlooked—Native American coastal shell-bearing sites.

The present research integrates geoarchaeological and zooarchaeological methods to investigate the process of archaeological site submergence and the interactions between coastal shell-bearing sites, sea-level rise, storm forcing, and tidal wetland migration in the Tampa Bay Estuary—Florida’s largest open-water estuary. By synthesizing stratigraphic, sedimentological, and zooarchaeological data from excavation units and sediment cores, we demonstrate that Indigenous shell-bearing sites are durable coastal features that influence the distribution and character of estuarine habitats. Our study adds to recent works highlighting the historical and contemporary ecological influence of Indigenous coastal terraforming within estuaries (e.g., Augustine and Dearden 2014; Groesbeck et al. 2014; Jackson et al. 2023a, b; Parkinson 2023). By demonstrating how shell-bearing sites are interwoven into the past, present, and future of Tampa Bay’s estuarine ecosystems, we endeavor to showcase their relevance as coastal habitats to estuary managers in Florida and beyond.

Methods

Study Area

Tampa Bay is an expansive (1000 km^2), albeit shallow (4-m mean depth) microtidal estuary on Florida’s central peninsular Gulf Coast (Fig. 1). The estuary is situated in a transitional zone between warm-temperate and tropical climates. This positioning and the estuary’s large size and salinity gradient support a highly diverse ecosystem of flora and fauna (Yates et al. 2011). Geologically, Tampa Bay is underlain by a series of collapsed sinkholes and karst sub-basins separated by bedrock highs that filled with sediment over its geologic history (Duncan et al. 2003; Hine et al. 2003, 2009). Rising Gulf waters flooded the mouth of the Tampa Bay depression approximately 8500 BP, allowing the establishment of wet prairie and marl marshes (Donahue et al. 2003; van Soelen et al. 2010). Continued sea-level rise permitted the expansion of these conditions throughout the remaining sub-basins, and by 5500 BP, estuarine waters were present in the northernmost depressions (Cronin et al. 2007). Jackson and colleagues (2023a) describe the establishment of paralic marshes in Upper Tampa Bay after ca. 4850 cal. BP, which kept pace with sea-level rises between 2.4 and 4.4 cm/century for approximately three millennia. After ca. 1885 cal. BP, the marshes were transgressed and converted to the sand flats and seagrass meadows that characterize much of the modern environment.

Archaeological fieldwork was completed at three precolumbian sites in Upper Tampa Bay, named Cabbagehead Bayou (CHB), Double Branch Bay (DBB), and Double Branch 21 (DB21). Upper Tampa Bay is a shallow sub-basin at the northwestern reaches of the estuary. Mosaics of tidal flats, seagrass meadows, oyster reef, salt marsh, and mangrove forests characterize the sub-basin, with shell-bearing archaeological sites comprising the seaward most supratidal landforms (Fig. 2). The three sites were first described in the late 1970s, though no subsurface testing was performed (Gluckman et al. 1978). We used minimally invasive excavation techniques to provide the first stratigraphic, zooarchaeological, and chronological documentation of the sites (Jackson et al. 2023a). CHB is small (0.7 ha) and semi-circular, with a maximum diameter

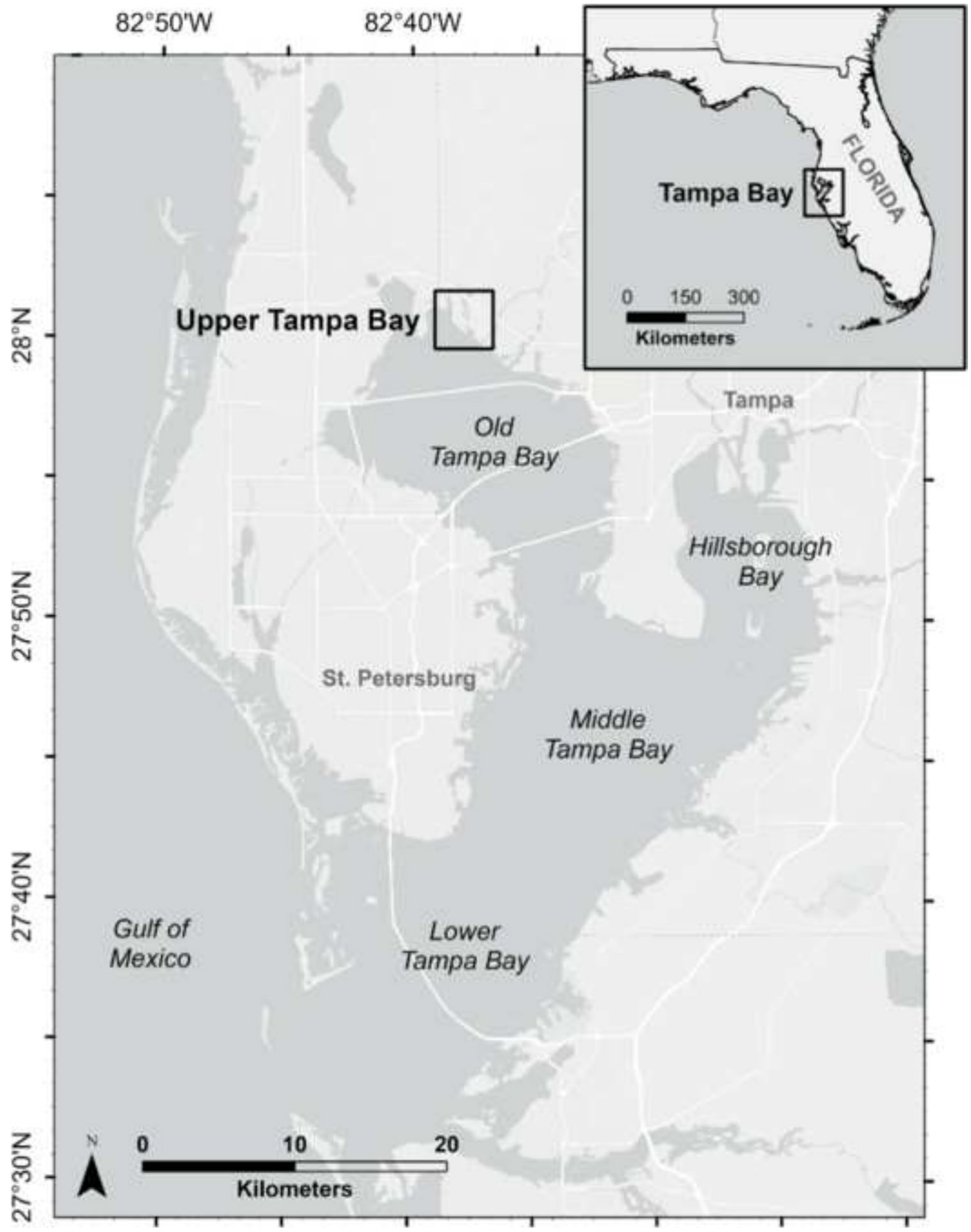

Fig. 1 Map of the Tampa Bay Estuary, Florida, USA, with Upper Tampa Bay and main bay segments identified

of 95 m and a maximum elevation of 1.4 m. DBB is linear, measuring approximately 125 m long and 10 m wide with an area of approximately 0.6 ha. Elevation steadily increases from sea level in the east to about 2 m tall at the western apex. Though CHB and DBB are islands today, our geoarchaeological work demonstrates that these were relic uplands adjacent to coastal marshes when human activities first began at the site (Jackson et al. 2023a). Tidal action likely started to interact with the shell-bearing sites around 1000 cal. BP. DB21 is a comparatively expansive (2 ha) site within the Upper Tampa Bay Park peninsula. The apex of the linear shell ridges along the southern edge of the site reaches about 1.5 m. Native peoples constructed and occupied this group of shell middens between 1500 and 700 BP.

Field Methods

A total of 16 percussion cores (PCs) were collected using 7.6-cm-diameter aluminum pipes along cross-shore transects to evaluate the subsurface stratigraphy in the intertidal zone seaward and landward near the apex of the shell-bearing sites (CBB $n = 6$, DBB $n = 4$, DB21 $n = 6$). Penetration depths of these cores ranged from 1 to 2 m. We excavated 13 small test units to investigate the stratigraphy and composition of the supratidal portions of the shellwork sites (CBB $n = 4$, DBB $n = 2$, DB21 $n = 7$). Supratidal excavation units measured 50×50 cm or 1×1 m in plan and were excavated in 10-cm levels to the maximum allowable depth (typically between 80 and

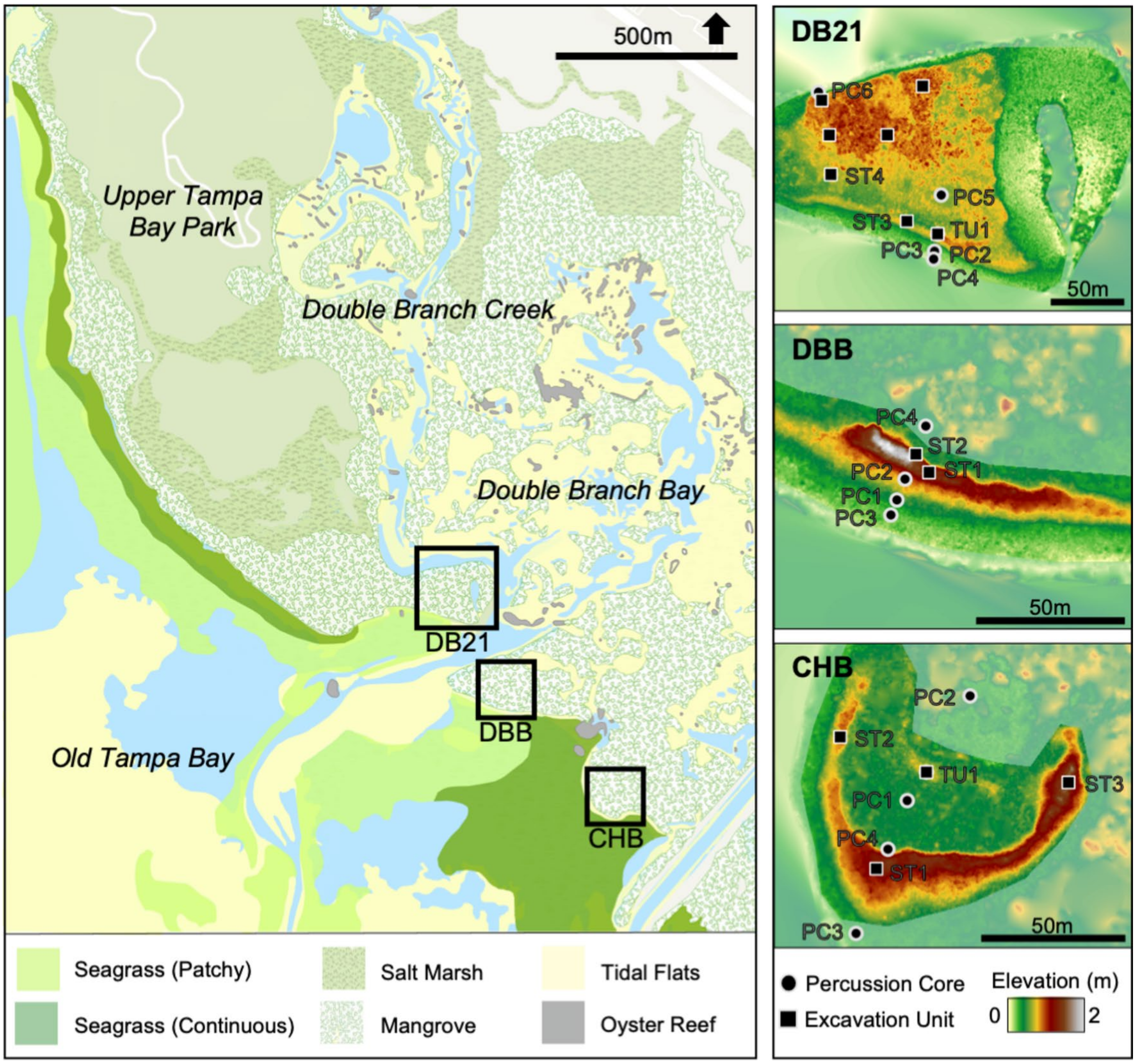

Fig. 2 Map of the Upper Tampa Bay project area with wetland habitats depicted (left) and shell-bearing sites with testing locations and elevational data (right). The elevation data within the approximate site boundaries are opaque, while the elevation data from the surrounding area is more transparent. Habitat data are compiled by the Southwest Florida Water Management District and Florida Fish and Wildlife Conservation Commission GIS portals. Elevation data is from light detection and ranging (LiDAR)-derived elevation models (ca. 2019)

100 cm). We screened sediment through 3.2-mm mesh to ensure the recovery of small faunal remains and artifacts. All left (i.e., bottom) valve oysters (*Crassostrea virginica*) and all non-oyster taxa were collected for laboratory analysis. Stratigraphic profiles exposed during excavations were mapped in the field and digitized upon return to the laboratory. Bulk sediment samples were collected from each recognized stratum for sedimentological analyses. Modern sediment analogs from salt marsh and mangrove habitats in Upper Tampa Bay were collected as part of a separate study (Jackson et al. 2021). We collected storm overwash sediment from the surface of CHB following Hurricane Eta in November 2020.

Laboratory Methods

Sedimentology and Stratigraphy

We followed standard methods to produce grain size distribution data (Balsillie 1995; Dean 1974; but see Jackson et al. 2023a). Briefly, samples were dispersed into a sodium hexametaphosphate solution (50 g/L) and agitated for 12 h. Samples were then wet-sieved through 63-μm mesh to separate coarse and fine fractions. Coarse fractions were dried and analyzed using sieves to yield percent composition values at 0.25-phi intervals. Mean grain size and sorting statistics were calculated by the method of moments following

Balsillie (1995). Total organic matter (TOM) and carbonate content were derived by sequential loss on ignition following Dean (1974). Samples (1.5 cm^3) were placed in pre-weighed ceramic crucibles and dried in an oven at 60 °C for 48 h and weighed to yield dry weight. Samples were then placed in a muffle furnace, heated to 550 °C for 5 h, and weighed again to measure the loss of mass (i.e., TOM). The samples were returned to the muffle furnace, heated to 900 °C for 5 h, and weighed a final time to yield $CaCO_3$ values.

Using the results of these analyses alongside the stratigraphic profiles, we identified five distinct facies: intact midden, storm-redeposited midden, mangrove, marsh, and aeolian sand. Grain size, sorting, and LOI data on sediments from contexts of aeolian sand ($n = 21$), mangrove ($n = 6$), marsh ($n = 7$), intact midden ($n = 15$), redeposited midden ($n = 15$), and storm overwash ($n = 1$) were transformed to z scores and analyzed using principal component analysis (PCA). We tested for differences in sediment compositions between facies using a multivariate analysis of variance (MANOVA).

Zooarchaeological Analysis

All invertebrate remains were identified to the lowest taxonomic classification possible. Non-repeating elements determined the minimum number of individuals (MNI) for each species and context. Species with fewer than five total observations and all contexts with fewer than 30 total identifications were removed prior to statistical analysis. We identified a total of 34,034 individual specimens representing 14 mollusk taxa and weighing approximately 212 kg. To examine broader changes in species compositions between contexts, we grouped the 14 invertebrate taxa into five general categories: oyster (*C. virginica*), large marine snails (*Neverita duplicata*, *Sinum perspectivum*, *Sinistrofulgur sinistrum*, *Melongena corona*, *Fulguropsis spirata*), small tidal zone snails (*Cerithium muscarum*, *Phrontis vibex*, *Littoraria* sp., *Melampus coffea*) terrestrial snails (*Polygyra* sp.), and rare taxa (*Geukensia granosissima*, *Crepidula* sp., *Urosalpinx* sp.). To test whether the invertebrate assemblages from intact and storm-redeposited midden contexts contained significantly different compositions, we used an analysis of similarity (ANOSIM). The ANOSIM test used the Bray-Curtis similarity index and was run using a permutation number of 9999. To identify which taxa contribute most to the variation between intact and redeposited contexts, we performed a similarity percentage (SIMPER) test. Mann-Whitney tests were enlisted to test the relationship between the MNI of small tidal zone snails and different site contexts. Because MNI tends to underrepresent larger or more fragile taxa (Reitz and Wing 2008:205-210), we also tested the relationship between the volumetric density of small tidal zone snails and site contexts. All quantitative analyses were performed in PAST v.4 (Hammer et al. 2001).

Geospatial Analyses

We enlisted geospatial analyses to estimate the scale of wetland encroachment on archaeological sites throughout the estuary. We digitized the shoreline of the Tampa Bay Estuary in ArcGIS Pro using 2022 aerial imagery. The generated shapefile included the natural and artificial shorelines of the estuary but did not extend into any of the major rivers. We created an arbitrary 1.5-km buffer inland to approximate the area expected to experience the greatest effects of sea-level rise by 2100 (Robison et al. 2020). We quantified the areas of land cover, wetland habitats, and archaeological sites within the buffer, and used the Intersect tool to define areas of overlap between these parameters.

Results

Stratigraphy

Drawing on field observations and laboratory analyses from the Native shell-bearing sites, we recognize three major types of stratigraphic profiles, which we refer to as intact midden, redeposited midden, and hybrid profiles (Fig. 3). Intact midden profiles, such as those from CHB, are high in organics and whole shell. Redeposited midden profiles, like those from DBB, have alternating medium-to-fine quartz sand beds with high concentrations of fragmented shell and small tidal zone snails—characteristics produced by wave forcing during storm events (Davis et al. 1989; Knowles and Davis 1991). Hybrid profiles, such as those from DB21, contain intact midden beneath storm-redeposited midden. Intact midden deposits range in thickness from 8 to 120 cm. At CHB, the intact midden deposits from the exterior shellwork are deflated—signaling that fine organic sediments have been oxidized and extracted by repeated inundation (Jackson et al. 2023a). These midden deposits differ from the interior of CHB and DB21, which exhibit considerably greater preservation of fine organics that produces a distinctive greasy sediment texture. Storm-redeposited midden deposits range in thickness from 26 to 81 cm. In the case of TU-1 at DB21, intact midden was observed below 42 cm of storm redeposited sediment (Fig. 4). Stratigraphic profiles within the percussion core transects document the accretion of mangrove peat atop shell midden in the intertidal zones of each site. Mangrove peat thickness ranges between 9 and 35 cm. The cores also illustrate the conversion of marsh habitat to mangrove forest. For example, PC3 at CHB has 18 cm of mangrove peat overlying 135 cm of marsh sediment seaward of

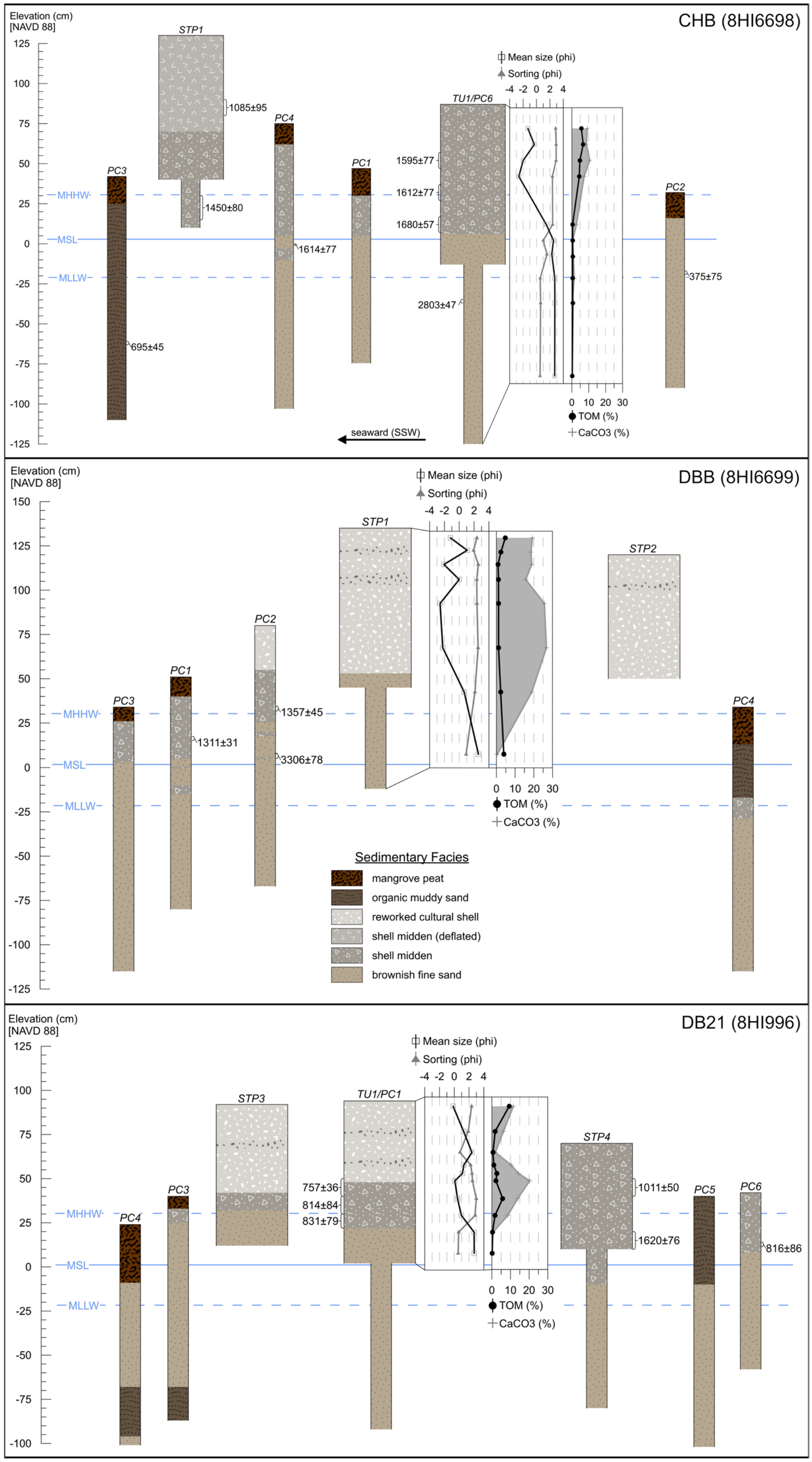

Fig. 3 Cross-sectional stratigraphic diagram of CHB, DBB, and DB21 illustrating sedimentary facies and differences between intact, redeposited, and hybrid stratigraphic profiles. Mean grain size and sorting data are presented alongside total organic matter and carbonate content. Testing locations are shown in Fig. 2. Radiocarbon dates are reported in calibrated years BP with 2-sigma error ranges. Tidal elevation data are from the Mobbly Bayou tide gauge (station id. 8726769)

Fig. 4 Excavation of TU1 at DB21. Note the sharp contact between storm redeposition and intact midden in profile, as well as the proximity to encroaching mangrove forest

the site, while PC4 at DBB has 22 cm of mangrove peat atop 28 cm of marsh sediment landward of the site. Aside from the deep marsh deposit evident in PC3 at CHB, the thickness of wetland facies tends to be greater in protected areas landward of the shell-bearing sites, nearing 50 cm thick at DBB (PC4) and DB21 (PC5). These landward wetland deposits are approximately 40 and 20 cm thicker than those along the seaward margins of DBB and DB21, respectively.

Sedimentology

Physical sedimentary characteristics of the five facies are summarized in Table 1 and Fig. S1. Owing to the unique depositional histories of each grouping, there were differences in the sediment compositions between groups ($F=22.2$, $df=36$, 192.9, $p=0.0001$; Table S1). PCA of mean grain size and LOI data on sediments from the three shell-bearing sites shows a distinct grouping of sedimentary facies (Fig. 5). Components 1 and 2 explain 84.6% of the variance in sedimentary composition. The loadings indicate that storm-redeposited midden may be differentiated from intact shell midden by greater medium sand, coarse sand, and very coarse sand content (Tables S2 and S3). Intact shell midden samples contain lesser sand fractions that are more poorly sorted and have greater organic and carbonate content. As expected, the redeposited midden group clusters near the sediment sample from Hurricane Eta, which has an extremely high medium sand content (83.6%). Marsh and mangrove also form fairly distinct clusters and are separated predominately by mud content, total organic matter, and mean grain size—all of which are greater in mangrove deposits.

Zooarchaeology

The shell-bearing sites in Upper Tampa Bay are composed predominately of oyster (84.4% of total MNI), with small tidal zone snails (6.8% of total MNI), terrestrial snails (3.8% of total MNI), large marine gastropods (3.7% of total MNI), and other taxa (1.3% of total MNI) forming the remainder of the species composition (see Table S4). Taxonomic richness ranged from 1 to 13 in intact midden deposits ($n=49$ samples) and from 4 to 13 in redeposited midden contexts ($n=28$ samples). Accordingly, mean taxonomic richness was lesser within intact shell midden (5.9) than redeposited midden (8.8). Oyster was the only species present in every site context ($n=77$ samples); *M. corona* ($n=68$ samples) and *N. duplicata* ($n=53$ samples) were the next most common species recovered. Dissimilarities in taxonomic compositions between intact and redeposited midden were driven by lesser oyster prevalence and greater abundance of *M. coffea* and *Littoraria* sp. in redeposited contexts ($R=0.6117$; $p=0.0001$) (Tables S5 and S6). *M. coffea* and *Littoraria* sp., along with two other small taxa (*C. muscarum* and *P. vibex*), were recovered in greater quantities ($U=24.5$; $p=0.0001$) and volumetric densities ($U=32$; $p=0.0001$) in redeposited strata (Fig. 6; Tables S7 and S8), reinforcing their observed association with storm events.

Geospatial Patterns

The stratigraphy within the percussion cores illustrates mangrove encroaching shell-bearing sites, and our geospatial analyses further highlight the scale of this process. Geospatial analyses revealed several land cover types extending 1.5 km from the shoreline (Table S9; Fig. S2). Urban and transportation comprise over 300 km^2 of this zone, by far the most of any other land cover. The zone contains more mangrove (51.27 km^2) than salt marsh habitat (10.4 km^2)—an imbalance that is expected to further increase alongside sea-level rise (Sherwood and Greening 2014). However, marsh habitat is present in considerable quantities in the Manatee and Little Manatee Rivers, which were not included in the geospatial analysis. Approximately 623 archaeological sites are recorded in the buffer zone. All the archaeological sites intersect with at least one land cover type, including urban ($n=424$ sites, 6.45 km^2), mangrove ($n=181$ sites, 1.19 km^2), upland forest ($n=98$ sites, 0.46 km^2), wetland forested mixed ($n=67$ sites, 0.19 km^2), agriculture ($n=42$ sites, 0.22 km^2), saltwater marsh ($n=41$ sites, 0.20 km^2), rangeland ($n=30$ sites, 0.03 km^2), and barren land ($n=5$ sites, 0.02 km^2). Our analysis reveals that wetland encroachment is likely occurring at approximately 247 sites (1.58 km^2). We also identified 93 archaeological sites comprising 1.22 km^2 that may be suitable for future wetland encroachment. These sites have little (< 10%) to no existing salt marsh, mangrove, and mixed forested wetlands within their boundary and no urban development. Most of these archaeological sites are currently in upland forest. The 93 sites are scattered throughout the estuary, though two denser concentrations are located within the uplands of Upper Tampa Bay and Terra Ceia State Park. There are undoubtedly additional archaeological sites that are currently unrecorded within this buffer zone that may be suitable for wetland migration. This omission, as well as the widespread underestimation of true site boundaries, suggests greater potential for mangrove recruitment atop shell-bearing sites. Ground-truthing the wetland and archaeological site data would be worthwhile.

Discussion

Sea-Level Rise and Mangrove Encroachment

Tampa Bay is among the most urbanized estuaries along the Gulf Coast, and given the limited area available for landward wetland migration, the bay's coastal wetlands are expected

Table 1 Summaries of the sedimentological data by facies

Facies/sub-facies	Mean size (phi)	Sorting (phi)	Gravel (%)	Very coarse sand (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Very fine sand (%)	Mud (%)	TOM (%)	$CaCO_3$ (%)
Aeolian sand (n = 21)											
Mean	2.66	0.69	0.8	0.24	0.59	7.77	66.86	19.3	4.44	0.68	0.54
Range	2.28–2.74	0.52–1.56	0–6.6	0–0.8	0.3–1.5	7–11.3	59.3–71.3	16.8–20.6	2.6–9.3	0–3.9	0–1.6
Standard deviation	0.1	0.3	1.6	0.3	0.3	1.0	2.9	1.2	1.4	1.0	0.5
Marsh (n = 7)											
Mean	4.57	0.87	0	0.4	1.86	9.83	53.9	16.9	17.1	7.67	0.86
Range	2.72–7.3	0.5–1.12	0	0–2	0–5.8	4.9–20.2	20.7–78.8	6.7–29.5	6.2–31.6	3.9–10.9	0.5–1.1
Standard deviation	2.2	0.2	0	0.7	2.2	5.1	21.2	9.7	9.5	2.5	0.2
Mangrove (n = 6)											
Mean	26.83	2.34	0	0	0.43	2.7	37.9	20.1	38.3	31.8	2.75
Range	3.55–49.4	0.7–3.5	0	0	0–2.6	0–8.7	14.9–48.3	7.8–29.1	28.7–67.2	17.8–49.4	0.7–3.5
Standard deviation	15.3	1.3	0	0	1.1	4.2	13.4	8.2	14.8	10.3	1.1
Intact midden (n = 15)											
Mean	−1.04	2.98	61.9	4.05	2.75	3.26	10.1	7.83	9.99	4.30	14.2
Range	−2.64–0.44	2.37–3.34	42.7–84.6	2.2–6.9	1.2–5.2	1.2–8.3	3.9–21.5	2–13.2	4.7–17.3	2.4–6.7	6.1–33.3
Standard deviation	0.8	0.3	10.9	1.6	1.1	1.7	4.7	3.4	3.0	1.4	8.6
Redeposited midden (n = 15)											
Mean	−0.08	2.23	40.7	4.34	4	19.6	23.4	4.66	3.35	2.86	16.3
Range	−2.59–2.39	0.77–2.89	1–78.8	1.4–11.6	1.4–9.3	6.1–40	6.1–67.1	0.3–13.9	0.9–10.2	0.6–9.7	1.9–29.1
Standard deviation	1.5	0.5	24.0	2.7	2.2	11.3	17.9	4.8	3.2	2.9	7.8
Storm overwash (n = 1)											
Mean	1.39	0.63	1.2	0.7	10.9	83.6	1.4	0.6	1.6	0.6	0.9
Range	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Standard deviation	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

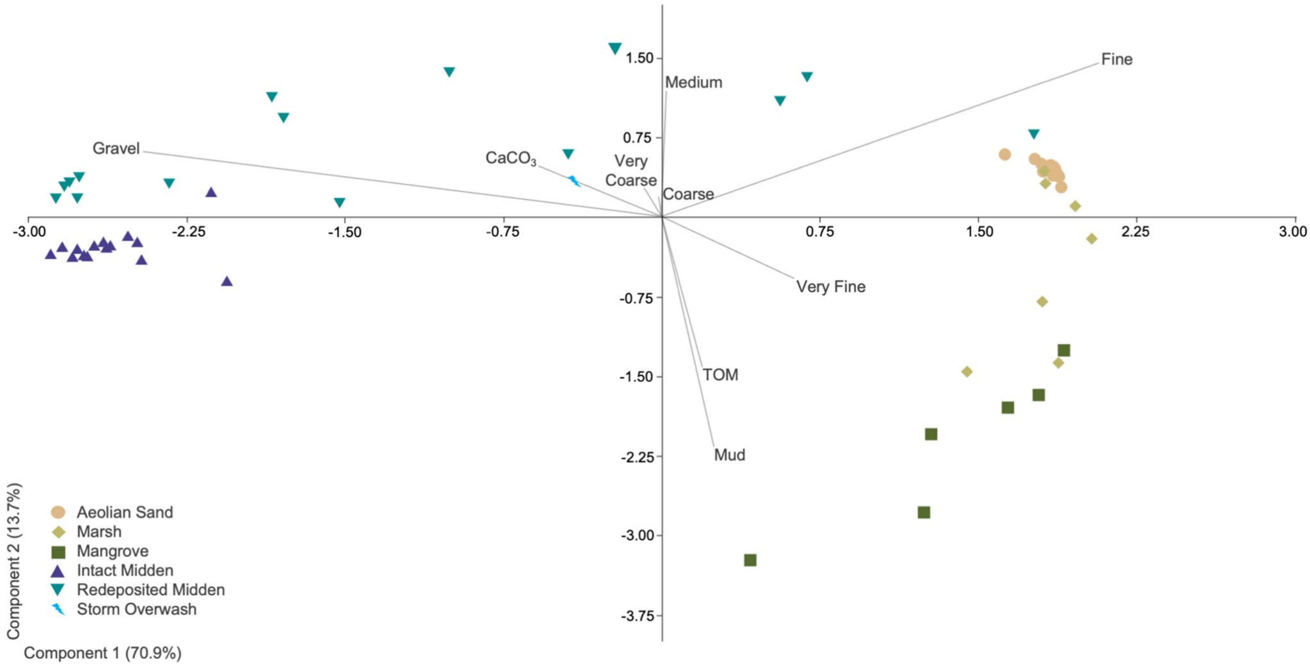

Fig. 5 PCA biplot showing separation between sedimentary facies based on differences in grain size, carbonate content, and LOI data

to experience significant losses as sea-level rises (Borchert et al. 2018; Geselbracht et al. 2015; Sherwood and Greening 2014). Water levels in Tampa Bay are approximately 20 cm higher than they were in 1946, and an additional 0.3 to 0.8 m is expected by the year 2050 (Tampa Bay Climate Science Advisory Panel 2019). The stratigraphy documented in this study demonstrates the ability of mangrove forests to keep pace with sea-level rise by encroaching marsh habitat and shell-bearing archaeological features—a process that may also increase the preservation potential for archaeological deposits (Fig. 8).

Climate change and anthropogenic alterations have led to major shifts in vegetation zonation throughout the Tampa Bay Estuary across the twentieth and twenty-first centuries (Jackson et al. 2021; Raabe et al. 2012). While we did not construct age-depth models for this study, other studies in the northern portion of the estuary describe a marsh-dominated system until the mid-twentieth century (Jackson et al. 2021; Raabe et al. 2012), and historic maps of the area support this chronology. Despite their recency, the mangrove-forest habitats on and around the shell-bearing sites in Upper Tampa Bay have deposited an average of

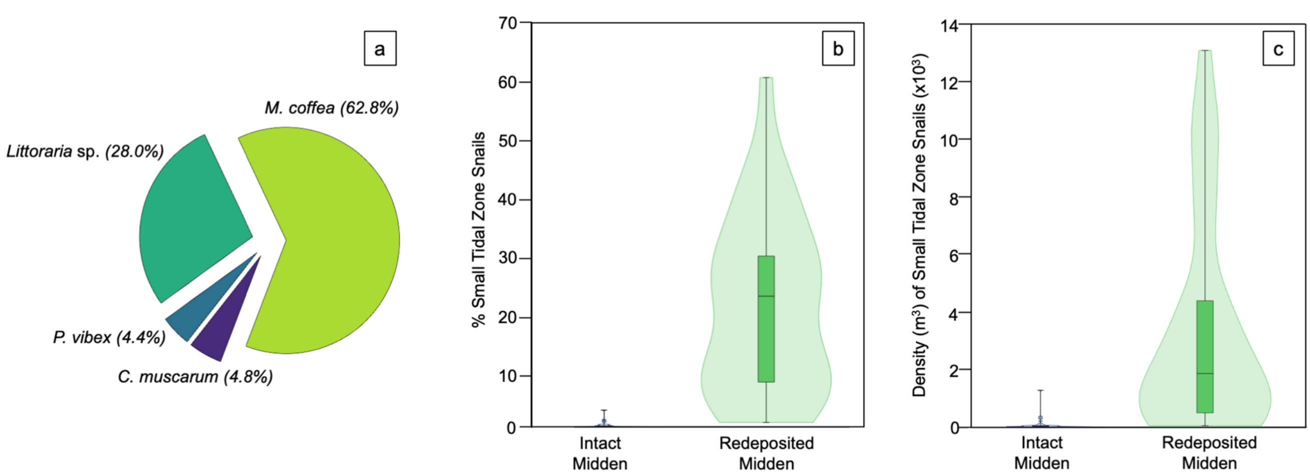

Fig. 6 Abundance (%) of the four small tidal zone snail species in the study (**a**) and violin-boxplots comparing the abundance (**b**) and volumetric densities (**c**) of small tidal zone snails in intact ($n=49$) and redeposited midden ($n=28$)

17.9 cm of peat in less than a century—probably closer to 60 years (0.29 cm/year). Further, recent research highlights the ability of mangrove forest to rapidly succeed oyster reefs in Tampa Bay (Hesterberg et al. 2022) and in the Mosquito Lagoon (McClenachan et al. 2020). Still, oyster reefs and shell-bearing sites are not directly analogous. In a living shoreline stabilization experiment along the Canaveral National Seashore, Donnelly et al. (2017) found that large midden shells may act as a barrier to the initial anchoring of mangrove propagules. However, once the propagule was anchored, survival and growth were high in shell midden matrix both in field and lab experiments. In their lab experiment, the authors found that mangrove roots could grow through and around shell, which they argue may add to the resilience of mangroves by providing them additional structure (Donnelly et al. 2017:399).

Native shell-bearing sites have been widely overlooked as a substrate for migrating coastal wetlands. Investigating the substrates that mangroves are capable of encroaching is important because subsurface sedimentary characteristics directly influence changes in the surface elevations of mangrove forests (Feher et al. 2022). Our study finds that approximately 250 archaeological sites in Tampa Bay have wetlands currently encroaching their boundaries. Moreover, many of these sites have additional topographic relief to provide migrating wetlands. Approximately 1.3 km^2 of marsh and mangrove habitats are currently within archaeological site boundaries, though this is likely a conservative estimate because of underestimated site boundaries discussed earlier. We also identified approximately 93 upland archaeological sites encompassing 1.22 km^2 that currently have little to no marsh or mangrove but may provide substrate for their future migration. Other upland substrates will provide greater total area for wetland migration in Tampa Bay, but this does not discount the past, present, and future role of Native shell-bearing sites as a contributor to this process.

Adaptive management initiatives that emphasize place-based approaches should be aware of this process and strive to integrate shell-bearing archaeological sites into estuary management planning. Our findings relate to specific goals of the Tampa Bay Estuary Program (TBEP) in seeking areas that allow the migration of emergent tidal wetlands to higher elevations (Sherwood and Greening 2014:410). Sea-level rise, mangrove forest encroachment, and peat accretion may thwart traditional archaeological testing, but site locations and extents should continue to be monitored. Most coastal archaeological studies related to sea-level rise have focused on erosional processes rather than sediment accretion via wetland interaction, which works to conceal sites (Chapman 2002). Land managers and scientists working in coastal wetlands should be aware of this process and make a vigilant effort to recognize archaeological features underlying tidal wetlands or composing coastal landforms.

We view the relationship between coastal shell-bearing sites and encroaching wetlands as mutualistic. Landward migrations of coastal wetlands will likely increase archaeological preservation potential in low-lying areas that would otherwise be scoured by sea-level rise and storm forcing. In turn, shell-bearing sites provide the needed topographic relief and durable substrate for migrating wetlands in areas where they would otherwise experience coastal squeeze.

Hurricane Taphonomy and Shell-Bearing Site Resilience

Hurricanes are expected to strengthen with the ongoing effects of climate change (Holland and Bruyère 2013; Scavia et al. 2002). Florida contends with hurricanes and tropical storms each year, typically between June and November. Hurricane and storm surge impacts are variable and depend on storm characteristics, such as size, direction of approach, speed, and point of landfall (Greening et al. 2006; Sallenger et al. 2006). Four recent hurricanes highlight this variability. For example, Hurricanes Ian (Category 4, 2022) and Irma (Category 4, 2017) generated negative surges of approximately 1.2 and 1.8 m in Tampa Bay, respectively, as the storms made landfall in southwest Florida and traversed the Florida peninsula to the east of Tampa Bay. Hurricane Idalia (Category 3, 2023) and Eta (Tropical Storm, 2020) generated positive surges of approximately 1.5 m, as they tracked offshore of Tampa Bay and made landfall in the Big Bend region to the north (Fig. S3). Both positive and negative surges can cause erosional forcing and sediment reworking (Cheng and Wang 2019). The last major landfall in the Tampa Bay Estuary was in 1921 when the Category 4 "Tarpon Springs Hurricane" released a 3.2-m storm surge into the estuary, leading to the loss of eight lives and causing over three million dollars in damages (Barnes 1998:103-108). Two previous major hurricane landfalls in Tampa Bay were documented in the nineteenth century (Ludlum 1963; Mohlman 1997), and the likelihood of additional storms of this magnitude or greater in the more distant past is quite high.

Small mollusk taxa provide additional insights into past storm events. Paleotempest studies often dichotomize nearshore and offshore mollusk taxa to identify hurricane overwash originating in marine environments (e.g., Ercolani et al. 2015; Jones et al. 2019). However, interpreting storm taphonomy at archaeological sites requires greater caution because past peoples were highly mobile and harvested fauna from various environments. Still, differences in mollusk shell compositions are informative for understanding paleoenvironments, particularly small incidental species (e.g., Holland-Lulewicz and Thompson 2021; Sassaman et al. 2022). Small intertidal zone snails are abundant within the fringing mangrove forest fronting the UTB sites today. During high-energy events, these species are dislodged from mangroves and rapidly buried by storm overwash sediment on the site. Thus, while small intertidal snails are rare within intact archaeological contexts, our results suggest that greater densities of *C. muscarum*, *P. vibex*, *Littoraria* sp., and *M. coffea* in subsurface contexts, particularly in association with bands of medium sand, serve as indicators of past storm events (see also Jackson et al. 2023a). Moreover, some of these small snail shells retain pigmentation, further suggesting they are recent inclusions that were rapidly buried.

While the three shell-bearing sites in our study have withstood centuries of hurricane landfalls, the geoarchaeological evidence presented in this study indicates that storm conditions may impact coastal shell-bearing archaeological sites in various ways. At DBB and DB21, wave forcing scours intact shell midden sediments and redeposits them landward. During this process, whole shells are tumbled leeward off the crest of the shell-bearing site, and sheets of medium sand, crushed shell, and small intertidal zone snails are deposited across the supratidal ground surface (Fig. 7). Thus, repeated storm forcing has produced the shore-parallel coastal berm morphology of DBB and DB21. Our sedimentary analysis at DBB suggests that the maximum site elevations (2 m) are storm generated. At CHB, no substantial redeposition was observed, but a large gash along the site's western edge is likely a product of erosion during past storms. A potential explanation for the greater resilience of CHB is that wind patterns during major hurricanes impacting Tampa Bay Estuary may direct wave forcing more northwestward, leading to more significant impacts at DBB and DB21. The greater shell density and semi-circular morphology of CHB may also make the site more resistant to repeated wave action.

While the positioning of these shell-bearing sites in the upper reaches of the estuary may shelter them from the stronger daily tidal forcing characteristic of the mouth and barrier islands, the magnitude of storm surges is simulated to be highest in the upper reaches of Tampa Bay (Weisberg and Zheng 2006, 2008). A contributing factor related to the magnitude of storm surge and wave generation is fetch distance—the unobstructed distance wind-driven waves traverse from their origin to where they break. Thus, obstructions limit fetch and the maximum wave heights produced by storms (Fagherazzi and Wiberg 2009). Hard structures, such as rock breakwaters, may be effective at attenuating wave energy in the short term but are costly and sometimes lead to the unintended loss of habitats (Gittman and Scyphers 2017; McQuarrie and Pilkey 1998; Schoonees et al. 2019). Living shorelines and artificial reefs are other stabilization methods that offer protection in various fetch conditions by attenuating wave energy and combatting sediment loss (Polk et al. 2022). Reef building organisms are also known to reduce hydrodynamic stress and alter sedimentation processes beyond the reefs themselves—some reporting measurable effects several hundreds of meters landward of the reef structure (Alonso et al. 2022; Donadi et al. 2013; Lunt et al. 2017; Meyer et al. 1997; Walles et al. 2015; van der Zee et al. 2012). Marshes can attenuate storm surges up to 25 cm/km depending on local hydrology and storm characteristics (Leonardi et al. 2018; Wamsley et al. 2010). Ysebaert and colleagues (2011) found salt marshes reduce wave height up to 80% over short distances (~50 m). Dense seagrass beds can attenuate wave heights up to 50% under some circumstances (Newell and Koch 2004). Lastly, a review of studies on mangrove wave attenuation rates by McIvor and colleagues (2012) found that 500 m of mangrove forest may reduce wave heights between 50 and 99%.

Like reefs, wetlands, and engineered structures, sedimentary and archaeological data from Upper Tampa Bay reveal that shell-bearing archaeological sites buffer storm forcing across landward wetland habitats, as well as modern urban infrastructure by attenuating wave energy. Much of the stratigraphy within the shell-bearing sites can only be produced by storm waves (Davis et al. 1989; Knowles and Davis 1991). The sedimentary characteristics and abundance of small intertidal mollusk shells indicate that these deposits would not exist without erosional impacts seaward of the sites—a process that absorbs wave energy and zeroes out fetch distance. Sediment cores taken landward of shell-bearing sites demonstrate that storm energy has been substantially attenuated because low energy deposits of fine sediment and peat are deeper and lack evidence of erosional processes. In contrast, cores taken seaward of shell-bearing sites exhibit clear evidence of shoreface erosion during high-water, high-energy events. The best example of this is at DBB, where storm redeposition is the greatest and mangrove and marsh deposits are considerably thicker landward of the shell-bearing site, but also DB21, where marsh and salt prairie habitats landward of the site have only recently begun to transition to mangrove forest (Fig. 8). Our interpretation of storm impacts is limited at CHB because this site did not bear the same evidence of sediment redeposition. The placement of our cores limits our ability to precisely define the scale of these effects in Upper Tampa Bay; however, by obstructing fetch, the shell-bearing structures fronting the sub-basin dampen energy that would otherwise be released on modern infrastructure approximately 1 km inland. Geoarchaeological work by Jackson et al. (2023a) correlates the construction of cultural shell-bearing sites and the conversion of late-Holocene estuarine environments to lower energy regimes at scales approximating 2 km in Lower Tampa Bay.

Fig. 7 Observed characteristics of storm impacts at shell-bearing sites in UTB. Stratigraphy reveals alternating bands of medium and fine sand beds with a high density of small tidal zone snails and crushed shell (PC2 from DB21) (left). Dense colonies of *M. coffea* fronting the seaward mangrove forest at DB21 (top right) get dislodged from mangroves during storm events and deposited on the site alongside storm sediment, while pushing whole shell landward (bottom right)

The dynamic relationship between storms, coastal wetlands, and shell-bearing sites should be further investigated. Storms are known to have variable impacts on mangrove forests—storm-redeposited sediments can provide topographic relief for wetlands to keep pace with sea-level rise or it may smother root systems—meanwhile, strong winds can uproot trees, snap branches and trunks, and damage the canopy (Barr et al. 2012; Smoak et al. 2013). Storm impacts may be immediate and delayed, as mangrove mortality has been documented in Florida up to 3 years following a hurricane—these impacts may also be species specific (Piou et al. 2006; Radabaugh et al. 2020). Our study provides evidence that storm impacts on shell-bearing sites are also storm and site dependent. Future studies on the topic would benefit from measurements and modeling of wave energy dissipation to provide a more quantitative approach suitable for comparison to other natural and artificial stabilization structures.

Fig. 8 Observed characteristics of mangrove encroachment in UTB. Representative stratigraphy of mangrove encroachment (left) showing mangrove peat above intact midden (PC4 from CHB). Mangroves recruiting the intertidal midden deposits (top right) and established forests fronting the seaward portion of the UTB sites (bottom right)

Managing the Future of the Past

Our research reveals a dynamic relationship between Indigenous shell-bearing archaeological sites, tidal wetlands, sea-level rise, and storms. These transformative relationships are not limited to Upper Tampa Bay, nor are they a strictly recent phenomenon (McFadden 2016; Parkinson 2023; Sassaman et al. 2016). Native shell-bearing sites contribute to resilient estuarine ecosystems by providing critical substrate and buffering storm forcing across landward wetland habitats and urban infrastructure (see also Jackson et al. 2023a, b). Shell-bearing sites should be understood as coastal habitats, whether they contain intact deposits or strata substantially reworked by coastal processes. Future work should examine how shell-bearing sites compare to living shorelines and other human engineered approaches in terms of their potential for energy buffering and wetland recruitment.

Indigenous peoples were living on the Florida peninsula over 14,500 years ago (Halligan et al. 2016) and inhabited the Tampa Bay region thousands of years prior to the evolution of modern estuarine conditions (Daniel and Wisenbaker 2017; Goodyear et al. 1983). For millennia, Native Americans terraformed the Florida coastline with massive volumes of mollusk shell and sand (Pluckhahn et al. 2015; Randall and Sassaman 2017; Saunders and Russo 2011; Schwadron 2017; Thompson et al. 2020; Wallis et al. 2015). Some extant shell mounds in the Tampa Bay Estuary stand over 10 m tall (Pluckhahn et al. 2021)—even larger mounds were mined away in the early twentieth century. Shell-bearing sites along the Gulf Coast are estimated to contain millions, and others, billions of oyster shells, which attests to the persistence of oyster fisheries guided by effective mariculture practices (Jenkins 2017; Reeder-Myers et al. 2022). The legacy of these stewardship systems and histories are embedded in the managed estuaries we study today.

There is a vital need to deliberate how to handle the challenges of climate change at archaeological sites within estuaries (Ayers-Rigsby et al. 2023). Archaeologists should be active partners with National Estuary Programs (NEPs). In Florida, for example, such partnerships might include the Florida Public Archaeology Network (FPAN). FPAN oversees programs related to archaeological site monitoring and climate change throughout the state, and their experience coordinating with coastal communities could be integrated into ongoing public restoration events and stakeholder meetings (Miller and Murray 2018). Still, archaeologists are not the only stewards of the past, and descendant communities should be involved in management discussions. For example, Florida NEPs could consult the Seminole Tribe of Florida, Miccosukee Tribe of Indians, Muscogee (Creek) Nation, and other federally recognized Tribal Nations. The recent development of TBEP's Social Science subcommittee is already provoking process changes within TBEP. For example, TBEP's equity decision support tool recommends consultation with archaeologists and Tribal Nations if any project is within 50 m of a recorded archaeological site. If the archaeological site is deemed eligible or potentially eligible for the National Registry (i.e., nationally significant) or if the site contains ancestral remains, the equity decision support tool advises that the project may be inequitable or inappropriate and, therefore, is not recommended for implementation (Simmons and Beck 2023; Tampa Bay Estuary Program 2023).

Despite the prevalence of shell-bearing sites in coastal areas worldwide, most of the Comprehensive Conservation and Management Plans of the 28 NEPs make no mention of archaeological resources or consultation with Tribal Nations or other descendant communities with coastal heritage at risk. While some NEPs mention preserving cultural heritage and inventorying cultural resources, these objectives are often vague and focus more on contemporary and historical Euro-American lifeways. We acknowledge that relationships between NEPs and Tribal Nations exist beyond management plans, and in some cases, we found evidence of partnerships that are not explicitly mentioned in Comprehensive Conservation and Management Plans. For example, the Barataria-Terrebonne National Estuary Program provides support to the Point-au-Chien Tribal Center for their Tribal Intergenerational Camp—focused on preserving their cultural heritage and sharing the value of wetland resources in their ancestral lands (Barataria-Terrebonne National Estuary Program 2019). Two notable examples of NEPs that describe collaborative efforts with Tribal Nations in their Comprehensive Conservation and Management Plans are the Peconic Estuary Partnership and the Puget Sound Partnership. The Peconic Estuary Partnership works with the Shinnecock Indian Nation to create climate vulnerability assessment and action plans to address prioritized climate change risks and vulnerabilities in the Shinnecock Indian Nation (Peconic Estuary Partnership 2020:48). The Puget Sound Partnership collaborates with several local tribes to co-manage treaty-protected resources. Traditional ecological knowledge is incorporated into science and policy within Puget Sound, and the estuary program describes tribal members as "indispensable partners" (Puget Sound Partnership 2018:38-39). We concur with the Seminole Tribe of Florida that cultures and environments must be recognized as a unified whole to make responsible and sustainable decisions (Heritage and Environment Resources Office 2022). We advocate for the NEPs to find ways to involve Tribal Nations with contemporary or ancestral ties to the watershed and other descendent communities with coastal heritage at risk, perhaps taking guidance from the NEPs that have successfully incorporated these collaborative efforts.

Conclusion

Sea-level rise and storms threaten coastal communities, habitats, and archaeological sites worldwide. Most of the research on these topics, particularly within archaeological scholarship, focuses on the destructive nature of these processes. Our intentions are not to minimize the severity of climate change impacts at coastal sites but to illustrate that destruction is not always the outcome of these processes, particularly in estuaries with deep histories of intensive coastal terraforming by Indigenous peoples. Like the interaction between storms and mangrove forests, which are sometimes beneficial and other times detrimental (Smoak et al. 2013), the same is true for archaeological sites. Storm and sea-level rise impacts are site-dependent—emphasizing the need for continued monitoring of these processes at archaeological sites. By understanding shell-bearing sites as dynamic intertidal habitats, our research reveals transformative interactions between archaeological features and sea-level rise, storm surge, and tidal wetland migrations in the Tampa Bay Estuary. We find that shell-bearing sites provide vital substrate for migrating coastal wetlands and that they buffer storm energy alongside these wetlands. Shell-bearing sites are durable features that have long been involved in estuarine biophysical processes (Augustine and Dearden 2014; Jackson et al. 2023a, b; Parkinson 2023). Their persistence over millennia under various climate change stressors and the benefits these sites continue to impart on coastal habitats and communities should inform coastal engineering projects intended to protect and expand coastal habitats. These findings warrant the incorporation of shell-bearing sites into NEP management plans and stronger collaborations between estuary managers, archaeologists, and descendent communities to manage the future of the past.

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Declarations

Conflict of Interest The authors declare no competing interests.

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