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Application of stable carbon isotopes for reconstructing salt-marsh floral zones and relative sea level, New Jersey, USA

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ABSTRACT: We investigated use of $\delta^{13}C$ in bulk organic sediment to define the botanical origin of samples preserved in coastal sediment as a means to reconstruct relative sea level in New Jersey, USA. Modern transects at three sites demonstrated that low and high salt-marsh floral zones dominated by C_4 species (*Spartina alterniflora* and *Spartina patens*) were associated with sediment $\delta^{13}C$ values between −18.9‰ and −15.8‰ and occurred from mean tide level (MTL) to mean higher high water (MHHW). Brackish transitional settings vegetated by *Phragmites australis* with *Iva fructescens* and *Typha* sp. (C_3 species) and freshwater upland samples (C_3 species) were characterized by bulk sediment $\delta^{13}C$ values of −27.0‰ to −22.0‰ and existed above MHHW. Parallel transects at one site suggested that intra-site variability was not discernible. The utility of $\delta^{13}C$ values for reconstructing relative sea level in New Jersey is limited by an inability to differentiate between brackish sediments related to sea level and freshwater upland samples. To facilitate this distinction in a 4.4 m core, we used a multi-proxy approach ($\delta^{13}C$ values with presence or absence of agglutinated foraminifera) to recognize indicative meanings for four sample types. Sediment with $\delta^{13}C$ values greater than −18.9‰ was derived from a vegetated salt-marsh and formed between MTL and MHHW. Sediment with $\delta^{13}C$ values less than −22.0‰ and containing agglutinated foraminifera formed in a brackish transitional zone between MHHW and highest astronomical tide (HAT). This is the narrowest elevational range of the four sample types and most precise sea-level indicator. Sediment with $\delta^{13}C$ values less than −22.0‰ and lacking foraminifera can only constrain the upper bound of former sea level. Samples with intermediate values (−22.0‰ to −18.9‰) formed between MTL and HAT. Using these indicative meanings and radiocarbon dates, we suggest that a transition from brackish to salt-marsh $\delta^{13}C$ values recorded in the core took approximately 350 years (from 1800 to 1450 cal. a BP). Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: stable carbon isotope; salt-marsh; New Jersey; sea level; *Spartina*.

Introduction

Stable carbon isotopes can determine the botanical and environmental origin of organic material preserved in coastal sediment (Chmura and Aharon, 1995; Tornqvist *et al.*, 2004; Wilson *et al.*, 2005a; Lamb *et al.*, 2006; González and Törnqvist, 2009). In temperate regions, the transition between freshwater, salt-marsh and marine settings presents a strong environmental and elevational gradient that is reflected in the stable carbon isotopic signature of plants and bulk organic sediments (Chmura *et al.*, 1987; Matson and Brinson, 1990; Goñi and Thomas, 2000). Reported $\delta^{13}C$ values are the ^{13}C:^{12}C ratio measured in samples and expressed in parts per mil (‰) compared to a standard reference material (Pee Dee Belemnite, PDB). During photosynthesis in land plants the Rubisco enzyme discriminates against $^{13}CO_2$ in favor of $^{12}CO_2$ and therefore concentrates the ^{12}C isotope. This fractionation of atmospheric carbon is recorded in living plant tissue and measured $\delta^{13}C$ values. The effect of this process is smaller in plants producing 4-carbon sugars (C_4 species) than in those producing 3-carbon sugars (C_3 species). Species using C_3 (Calvin–Benson) and C_4 (Hatch–Slack) photosynthetic pathways are associated with $\delta^{13}C$ values of −34‰ to −23‰ and −17‰ to −9‰ respectively (Chmura and Aharon, 1995; Lamb *et al.*, 2006). Along the temperate northeast and mid-Atlantic coasts of the USA, salt-marshes are predominantly vegetated by grasses (e.g. *Spartina* spp.) utilizing the C_4 pathway (Middleburg *et al.*, 1997; Johnson *et al.*, 2007; Tanner *et al.*, 2007). Occurrences of C_3 plants such as *Salicornia* spp. and *Juncus* spp. on southern New Jersey salt-marshes are restricted to patches of limited extent and persistence. In contrast, freshwater uplands above the limit of tidal inundation are associated with C_3 plants (Middleburg *et al.*, 1997; Lamb *et al.*, 2006). As the dominant input to salt-marsh sediments is likely derived from vascular vegetation (Chmura and Aharon, 1995; Malamud-Roam and Ingram, 2001; Lamb *et al.*, 2006), bulk sediment $\delta^{13}C$ values are a proxy for the dominant vegetation at the time of deposition (Malamud-Roam and Ingram, 2004). However, bulk sediment $\delta^{13}C$ measurements also include allochthonous material derived from fresh, brackish or marine environments as either dissolved or particulate matter (Lamb *et al.*, 2006; Gebrehiwet *et al.*, 2008). This allocthonous material can have $\delta^{13}C$ values of −12‰ to −33‰ (Lamb *et al.*, 2006). Further difficulties arise from C_3 plants that are tolerant of tidal submergence (e.g. *Juncus roemerianus*), which limits use of this technique on the southeastern and Gulf coasts of the USA where C_3 species dominate both freshwater upland and salt-marsh environments, making them indistinguishable from one another on the basis of bulk sediment $\delta^{13}C$ values alone (Chmura and Aharon, 1995; Kemp *et al.*, 2010).

The ability to differentiate sediments derived from salt-marsh and freshwater upland environments presents a means to use $\delta^{13}C$ values as a sea-level indicator by recognition of these floral environments in organic sedimentary sequences (Wilson *et al.*, 2005b; Lamb *et al.*, 2007). This approach is applicable where C_3 and C_4 plants have existed (with different and unchanged distributions) over the period under consideration

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(Wilson *et al.*, 2005a) and requires understanding of the influence of post-depositional diagenesis on $\delta^{13}C$ values (DeLaune, 1986; Ember *et al.*, 1987; Fogel *et al.*, 1989). The precision of this approach is increased if salt-marshes are further divided using $\delta^{13}C$ values into floral zones (high and low salt-marsh) characterized by varying proportions of C_3 and C_4 inputs. To be used as a sea-level indicator, it is necessary to quantify the relationship between bulk sediment $\delta^{13}C$ values (or the vegetation communities they represent) and tidal elevation (Shennan, 1986; van de Plassche, 1986). This relationship is formalized by the indicative meaning, which is the elevational range occupied by a sea-level indicator (indicative range) in relation to a contemporaneous tide level (reference water level).

In this study, we investigate use of $\delta^{13}C$ from bulk organic sediments to identify floral zones and to be used as a sea-level indicator in southern New Jersey, USA. Vegetation communities and measured $\delta^{13}C$ values of modern (surface) bulk sediments along salt-marsh transects at three study sites (Fig. 1) are described, including replicate transects at one site (Leeds Point) to investigate intra-site variability. This modern dataset is used with foraminiferal data (Kemp *et al.*, 2011) to interpret $\delta^{13}C$ values measured in a 4.4 m core of organic sediment with preliminary radiocarbon dating as changes in floral composition. This application provides a means to consider the strengths and limitations of bulk sediment $\delta^{13}C$ values as sea-level indicators in southern New Jersey salt-marshes and similar regions.

Study area

The southern Atlantic coast of New Jersey is characterized by barrier islands separating a back-barrier lagoon system from the open ocean. The coast between Great Bay and Cape May (Fig. 1) includes nine inlets between barrier islands that typically decrease in size from north to south along the coast (Ferland, 1990). These inlets facilitate exchange of water between the Atlantic Ocean and lagoons. Large areas of formerly open-water lagoon have been infilled by accretion of salt-marsh and estuarine sediment (Daddario, 1961; Meyerson, 1972; Thorbjarnarson *et al.*, 1985; Psuty, 1986; Ferland, 1990). The resulting sequences of sediment provide archives of relative sea level (RSL) and environmental change. Rates of glacio-isostatic subsidence in southern New Jersey are amongst the highest on the US Atlantic coast and are about 1.2–1.8 mm a^{-1} (Engelhart *et al.*, 2011a,b). According to Miller *et al.* (2009), RSL rise from 5000 to 500 a BP averaged 1.8 mm a^{-1}. Around Great Bay, Psuty (1986) reconstructed approximately 8.3 m of RSL rise in the last 5200 years.

Modern salt-marshes in this region form extensive platforms. Tidal flats are rare as the coast is experiencing erosion (Dolan *et al.*, 1979; Fitzgerald *et al.*, 2008). A low-marsh floral zone of *Spartina alterniflora* (tall form) is frequently present, while high-marsh zones are characterized by *Spartina patens*, *Spartina alterniflora* (short form) and *Distichlis spicata* (Daddario, 1961). Other species are infrequently found in the high salt-marsh zone and constitute a small proportion of the plant community by area. The border between salt-marshes and freshwater upland is vegetated by *Phragmites australis* and *Iva fructescens*, with occurrences of *Typha* sp. and *Scirpus* sp. This zone is typically narrow and represents brackish conditions (Daddario, 1961; Stuckey and Gould, 2000).

Tidal ranges (mean lower low water, MLLW, to mean higher high water, MHHW) are slightly larger on the ocean side of the barrier islands (1.4 m at Atlantic City; Fig. 1) than in the lagoons. Tidal ranges estimated by VDatum (Yang *et al.*, 2008) were 1.1 m at Leeds Point and Bass River and 1.3 m at Brigantine Barrier.

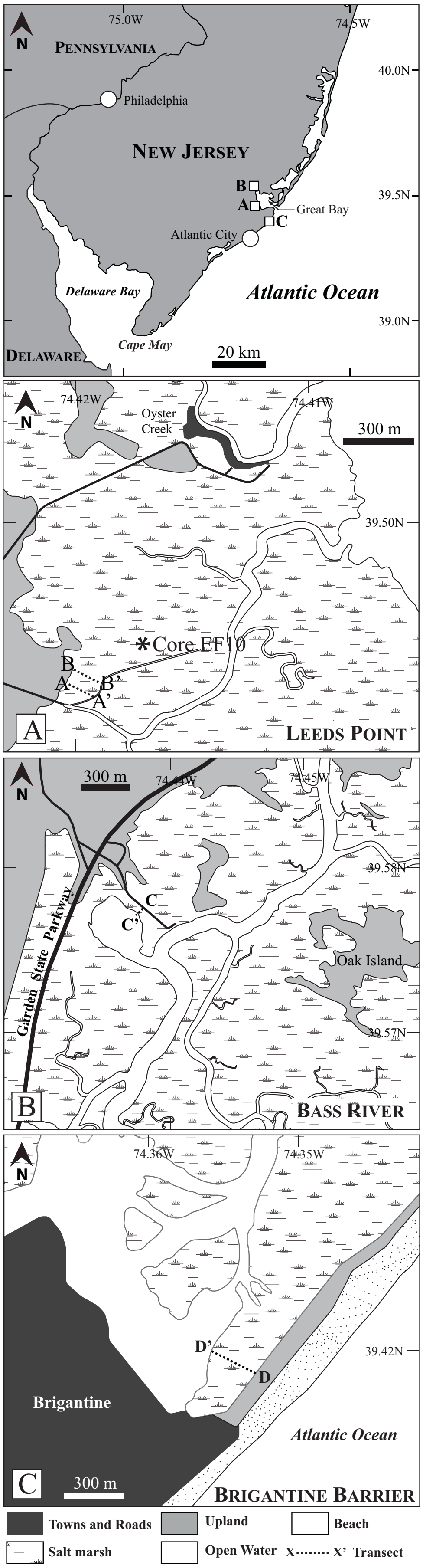

Figure 1. Location of study sites in southern New Jersey (USA) at (A) Leeds Point, (B) Bass River and (C) Brigantine Barrier. Surface (0–1 cm) sediment samples were collected for analysis of $\delta^{13}C$, C:N and total organic carbon along transects at each site. A core (EF10) was recovered from Leeds Point for analysis (A).

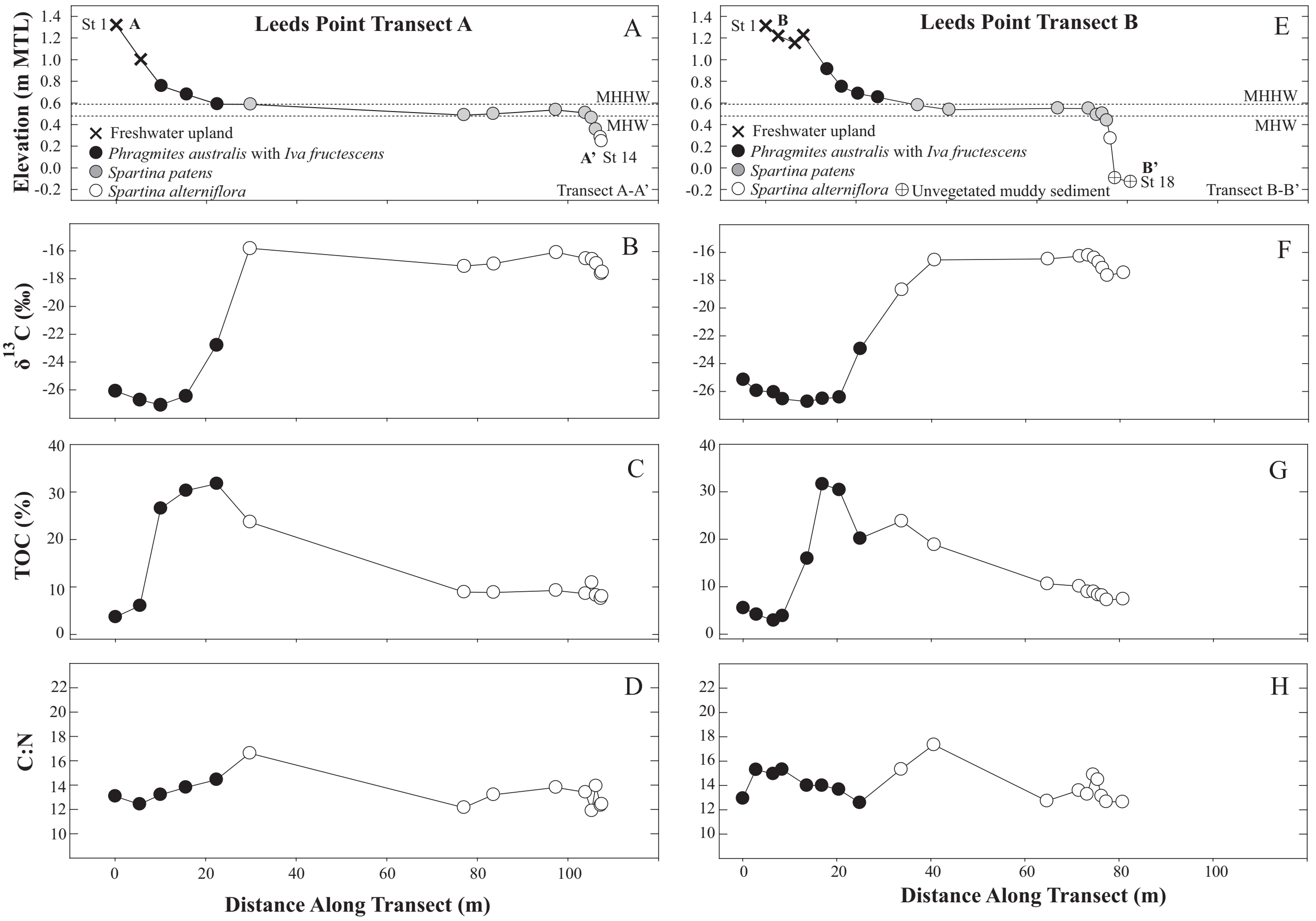

Figure 2. Transects (A–A′ and B–B′) from Leeds Point. Left panels show results from transect A; right panels show results from transect B. (A, E) Elevation profiles of transects including plant zonation; (B, F) measured $\delta^{13}C$ values from bulk surface sediment samples; (C, G) total organic carbon (TOC); and (D, H) C:N ratios. Filled and open circles represent samples with $\delta^{13}C$ values associated with C_3 and C_4 photosynthetic pathways, respectively. In each panel, the error associated with each measurement is smaller than the symbol used. MHW, mean high water; MHHW, mean higher high water.

Leeds Point is on the west side of Great Bay (Fig. 1). Salt-marshes in this area frequently exceed 1 km in width (Ferland, 1990). We sampled two transects (A–A′ and B–B′; Figs 1A and 2A) that extended from freshwater upland, through a narrow (10–20 m wide) brackish zone vegetated by *Phragmites australis* and *Typha* sp., a wide (up to 100 m) high-marsh floral zone of *Spartina patens* with *Spartina alterniflora* (short form) and a narrow (less than 10 m) low-marsh floral zone bordering a tidal channel characterized by low-density stands of *Spartina alterniflora* (tall form) and unvegetated muddy sediment. Core EF10 was collected at Leeds Point in the high salt-marsh (Fig. 1A).

We established a 50 m long transect (C–C′) at the confluence of Bass River with Great Bay (Fig. 1). The transect ran from a brackish, transitional (salt-marsh to upland) zone of *Phragmites australis*, through a high-marsh floral zone dominated by *Spartina patens* and *Spartina alterniflora* (short form) and into a narrow (less than 10 m wide) low-marsh zone of tall-form *Spartina alterniflora* (Figs 1B and 3A).

The Brigantine Barrier site is a back-barrier salt-marsh (Fig. 1C). A 120 m transect (D–D′) encompassed the brackish transition from freshwater upland to salt-marsh dominated by *Phragmites australis* and *Iva fructescens* (less than 10 m wide), a high-marsh zone defined by *Spartina patens* and *Spartina alterniflora* (short form) and a low-marsh zone of patchy *Spartina alterniflora* (tall form) and exposed muddy sediment (Fig. 4A).

Modern salt-marsh foraminifera at the three study sites were described by (Kemp *et al.*, 2011). Foraminifera were absent in freshwater upland sediments along the landward edges of salt-marshes (Scott and Medioli, 1978; Gehrels, 1994; Edwards *et al.*, 2004). The brackish zone of *Phragmites australis*, *Iva fructescens* and *Typha* sp. was inhabited by *Haplophragmoides manilaensis* or *Jadammina macrescens* with *Trochammina inflata*. High-marsh floral environments were dominated by *Arenoparrella mexicana* and *Tiphotrocha comprimata*. Low-marsh floral zones were uniformly dominated by *Miliammina fusca*.

Methods

Sampling regime

Transects across the three modern salt-marshes were positioned to include the range of physiographic environments at each site. Sampling stations reflected changes in elevation and vegetation. We collected bulk surface (0–1 cm) sediment for analysis at each station. Two parallel transects at Leeds Point were used to consider the influence of intra-site variability. Sample elevations were established using real time kinematic (RTK) satellite navigation with a minimum of 2000 base station observations (Leica GPS 1200+). Individual samples were leveled to base stations using a total station. Elevations were converted from orthometric to tidal datums by VDatum. Elevations were expressed as a standardized water-level index (SWLI) to allow comparison among sites with different tidal ranges (Horton and Edwards, 2006). We collected examples

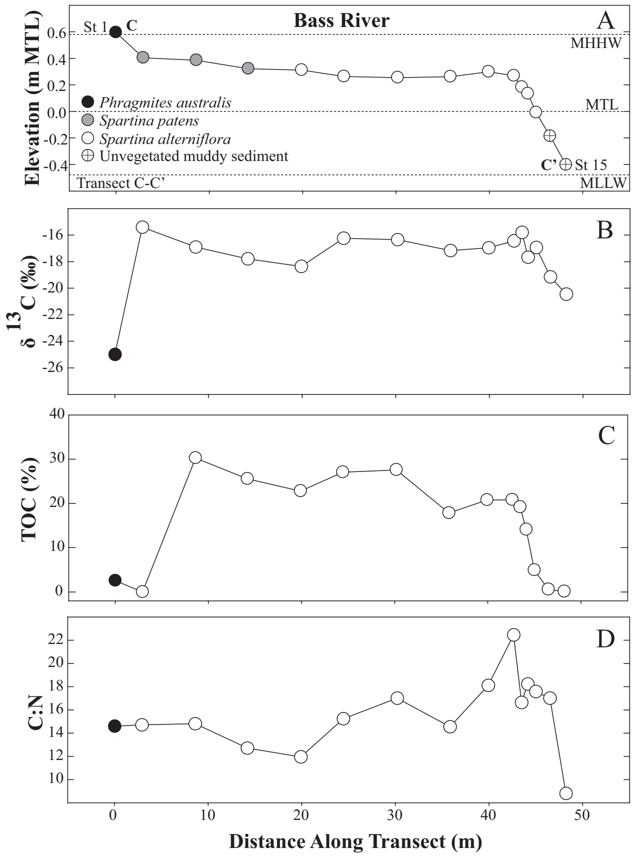

Figure 3. Transect C–C′ at Bass River. (A) Elevation profile of the transect including plant zonation; (B) measured $\delta^{13}C$ values from bulk surface sediment samples; (C) total organic carbon (TOC); and (D) C:N ratios. Filled and open circles represent samples with $\delta^{13}C$ values associated with C_3 and C_4 photosynthetic pathways respectively. In each panel, the error associated with each measurement is smaller than the symbol used.

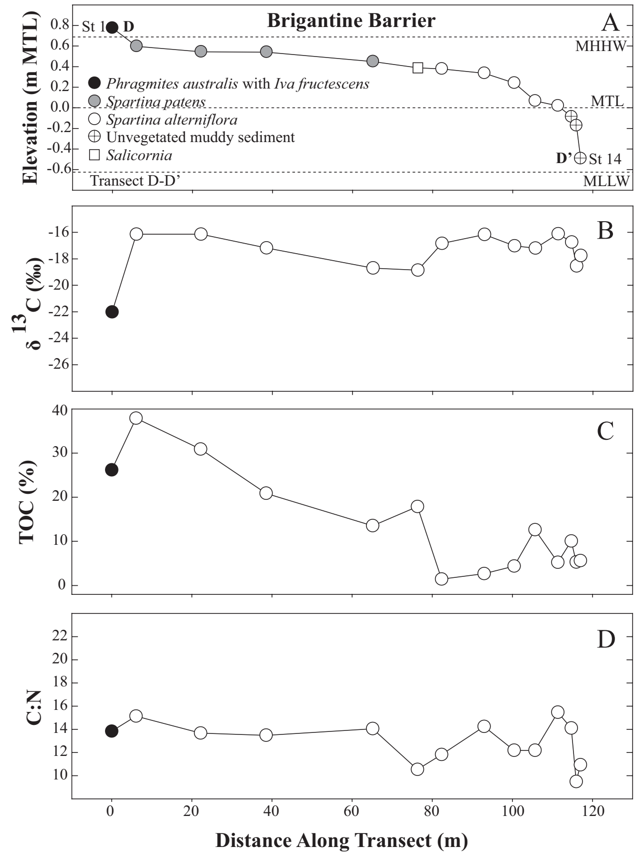

Figure 4. Transect D–D′ at Brigantine Barrier. (A) Elevation profile of the transect including zonation of vascular vegetation; (B) measured $\delta^{13}C$ values from bulk surface sediment samples; (C) total organic carbon (TOC); and (D) C:N ratios. Filled and open circles represent samples with $\delta^{13}C$ values associated with C_3 and C_4 photosynthetic pathways respectively. In each panel, the error associated with each measurement is smaller than the symbol used.

(leaf and stem) of living salt-marsh plants (short-form *Spartina alterniflora, Spartina patens* and *Phragmites australis*) from Leeds Point for comparison with measured bulk sediment $\delta^{13}C$ values at stations where these species were the dominant vegetation.

Core EF10 was selected for analysis from Leeds Point following stratigraphic investigation. It was recovered in 50 cm sections using a Russian-type hand core and sampled at 5 cm resolution in the laboratory. Each core sample was 1 cm thick.

Preparation and measurement of stable carbon isotopes

Bulk sediment samples (modern transects and core) were prepared for measurement of $\delta^{13}C$, percent total nitrogen (%N), percent organic carbon (%C) and total organic carbon (TOC) by treatment with 5% HCl for 18 hours and then washed with deionized water. Plant samples were washed with deionized water to remove sediment particles. All samples were oven-dried at 40°C and milled to a fine powder using a pestle and mortar. Analysis of %C, %N and TOC was performed by combustion in a Costech elemental analyzer coupled online to an Optima dual-inlet mass spectrometer. Reported $\delta^{13}C$ values were calculated to the Vienna Pee Dee Belemnite (VPDB) scale using a within-run laboratory standard (cellulose, Sigma Chemical prod. no. C-6413). In each run of 50 samples, approximately 10 replicates of laboratory standard BROC2 were analyzed. Its $\delta^{13}C$ value (compared to VPDB) was derived from regular comparison with international calibration and reference materials (NBS-18, NBS-19 and NBS-22). Accuracy of measured $\delta^{13}C$ values was checked by analyzing BROC2 and an unknown sample (previously run against NBS). Comparisons were always within 0.1‰ and confirm that measured $\delta^{13}C$ values are accurate. Sample %C and %N were analyzed on the same instrument and C:N ratios were calibrated through an acetanilide standard. C:N results are presented on a weight-to-weight basis. Replicate analysis of well-mixed samples indicated precision of $\pm$<0.1‰ for $\delta^{13}C$ (1σ). Precision of nitrogen measurements was ±0.16% (1σ). Results for modern bulk sediment are reported in Supporting information, Table S1.

We used the rinse method for measuring $\delta^{13}C$, %C, %N and C:N. The most common alternatives are acid fumigation and acidification in a silver capsule. A recent study comparing these methods concluded that the rinse method could introduce non-systematic variability including offsets of $\delta^{13}C$ values caused by loss of fine-grained material and inorganic carbon (Brodie *et al.*, 2011). Significantly, variability was also reported for $\delta^{13}C$ measurements using the alternative approaches. This study included the BROC2 standard that we used. Consistent and reproducible measurements give confidence that our method is robust and appropriate.

Radiocarbon ages

Five samples from core EF10 were radiocarbon dated. Each sample was cleaned under a microscope to remove contaminating material such as adhered sediment or invasive younger roots and dried at <50°C. Radiocarbon ages were calibrated individually using Calib 6.0.2 (Stuiver and Reimer, 1993) and the IntCal09 calibration curve. We report original radiocarbon ages and calibrated dates (with 2σ calibrated uncertainty), expressed by convention as years before present (BP), where zero is AD 1950 (Stuiver and Polach, 1977).

Results

Characterization of modern salt-marsh plants and sediments

Three salt-marsh floral zones were present at each of the study sites. The narrow, transitional zone of *Phragmites australis* (often with *Typha* sp. and *Iva fructescens*) occurred above mean higher high water (MHHW). No upper limit was established for this community because *Phragmites australis* also occurs throughout the study region at sites without marine influence such as freshwater marshes and the periphery of lakes and ponds. High-marsh floral zones of *Spartina patens*, *Distichlis spicata* and *Spartina alterniflora* (short form) were dominant between MHHW and mean high water (MHW). Averaged measurements of the modern boundary between high-marsh and brackish transitional floral zones at Leeds Point ($n = 88$) located it within 2 cm of MHHW. Low-marsh floral zones characterized by *Spartina alterniflora* (tall form) were present from MHW to mean tide level. At Leeds Point, 70 averaged measurements of the modern boundary between *Spartina alterniflora* and the high-marsh floral zone confirmed that it occurred within 1 cm of MHW with a $\pm 1\sigma$ confidence interval of 6 cm.

The $\delta^{13}C$, C:N and TOC composition of modern salt-marsh sediments was measured in 61 surface samples collected at the three study sites. Along Leeds Point transect A (Fig. 2A–D), samples from freshwater upland and *Phragmites australis* with *Iva fructescens* environments had $\delta^{13}C$ values from −27.0‰ to −22.7‰, TOC of 4–32% and C:N ratios of 12.4–14.4. Samples from zones of *Spartina patens* and *Spartina alterniflora* recorded $\delta^{13}C$ values from −17.5‰ to −15.8‰, TOC between 7.5% and 23.6% and C:N ratios from 12.1 to 16.6 (Fig. 2). On transect B (Fig. 2E–H), samples from freshwater upland and *Phragmites australis* with *Iva fructescens* environments recorded $\delta^{13}C$ values from −26.7‰ to −22.9‰, TOC of 3–32% and C:N ratios of 12.9–15.3. Measured $\delta^{13}C$ in *Spartina patens*, *Spartina alterniflora* and muddy unvegetated zones varied from −18.7‰ to −16.2‰, with TOC of 7–24% and C:N ratios of 12.6–17.3.

Parallel transects at Leeds Point had consistent $\delta^{13}C$ values. Sediments from C_3 floral zones on both transects had an average $\delta^{13}C$ of −25.8‰. High- and low-salt-marsh floral zones on transect A–A′ yielded an average $\delta^{13}C$ value of −16.7‰ (−17.6‰ to −15.8‰). On transect B–B′ they averaged −16.8‰ (−17.6‰ to −16.2‰). Similarity between bulk sediment $\delta^{13}C$ values along these suggests that small-scale spatial variability was not significant, although this consistency should be confirmed by replicate sample design at additional sites.

At Bass River (Fig. 3), a sample in a *Phragmites australis* stand had a $\delta^{13}C$ value of −25.0‰, TOC of 2.6% and C:N ratio of 14.6. Samples collected in *Spartina patens*, *Spartina alterniflora* and muddy unvegetated sediment zones had $\delta^{13}C$ values of −20.5‰ to −15.4‰, TOC values of 0–33% and C:N ratios of 8.8–22.4 (Fig. 3).

The Brigantine Barrier transect included one sample situated in a *Phragmites australis* and *Iva fructescens* stand that had a $\delta^{13}C$ value of −22.0‰, TOC of 26.2% and C:N ratio of 13.8 (Fig. 4). Samples in a mixed zone of *Spartina patens*, *Spartina alterniflora* and *Salicornia* spp. had $\delta^{13}C$ values of −18.9‰ to −16.1‰, TOC of 1–38% and C:N ratios between 10.5 and 15.5. Three samples from muddy unvegetated sediment had $\delta^{13}C$ values of −18.5‰ to −16.5‰, TOC of 5–10% and C:N ratios between 9.5 and 14.1 (Fig. 4).

We measured $\delta^{13}C$, TOC and C:N in stems and leaves from single examples of salt-marsh plants collected at Leeds Point (Fig. 5A). The *Spartina alterniflora* (C_4 photosynthetic pathway) specimen had $\delta^{13}C$ values of −12.4‰ and −13.0‰ for its stem and leaf respectively, with TOC of 38.7% and 43.1% and C:N ratios of 92.9 and 35.5. *Spartina patens* (C_4 photosynthetic pathway) stem material had a $\delta^{13}C$ value of −13.8‰, TOC of 43.7% and C:N of 52.9. A leaf from the same plant yielded a

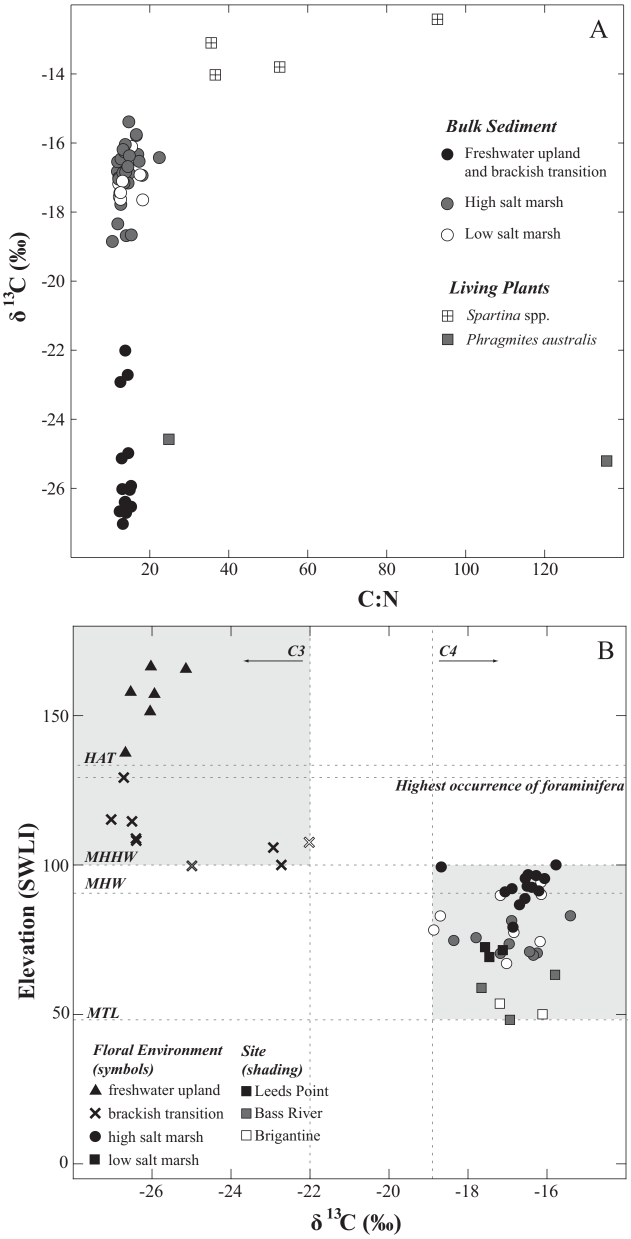

Figure 5. (A) $\delta^{13}C$ and C:N values in bulk organic sediment from vegetated sampling stations and stems and leaves of living plants. (B) Relationship between elevation and measured $\delta^{13}C$ values in bulk organic sediment from vegetated sampling stations at three modern salt-marshes. Elevations are expressed as a standardized water-level index (SWLI), where 100 is MHHW and 0 is MLLW. Tidal datums shown for reference. Symbols represent floral environment and symbol shading denotes site. Gray regions show elevation and $\delta^{13}C$ thresholds used for defining environmental origin. HAT, highest astronomical tide; MHHW, mean higher high water; MHW, mean high water; MTL, mean tide level. Value used for HAT is from the Atlantic City tide gauge.

δ^{13}C value of −14.0‰, TOC of 29.9% and C:N of 36.6. An example of *Phragmites australis* (C_3 photosynthetic pathway) recorded stem and leaf δ^{13}C values of −25.2‰ and −24.6‰ respectively. TOC measured from stem material was 47.5% compared with 41.9% in the leaf. C:N ratios were 135.7 in the stem and 24.8 in the leaf.

Characteristics of bulk sediments and foraminifera in core EF10

The base of EF10 consists of sand and gravel (Fig. 6). This unit is overlain by unstructured, organic-rich sediment from 4.2 to 3.2 m. Sediment between 3.2 and 0.8 m is characteristic of a salt-marsh. The upper 0.8 m is organic silt that likely reflects anthropogenic modification of the site (e.g. ditching). Agglutinated foraminifera typical of New Jersey salt-marshes were present above 3.95 m. We measured δ^{13}C, TOC and C:N in 91 bulk sediment samples from the upper 4.2 m of core EF10 (Fig. 6). From 4.20 to 3.35 m δ^{13}C values varied from −26.8‰ to −22.2‰. Between 3.35 m and 2.80 m there was a trend toward higher δ^{13}C values; the ten samples in this interval varied from −24.8‰ to −19.1‰. There was little δ^{13}C variability in the upper 2.80 m, where measured values varied from −16.2‰ to −13.1‰. TOC increased between 4.20 and 3.40 m from 3% to 39.5%. A reversal of this trend was observed between 3.40 and 2.40 m, with TOC values that decreased from 39.5% to 8.6%. In the upper 2.40 m of the core TOC increased to a peak of 32.8% at 1.40 m and averaged 18.3%. There was no clear trend in C:N ratios, which varied from 13.8 to 32.8 (average 20.9), with the exception of two anomalous data points at 0.80 m (C:N of 45.7) and 0.05 m (C:N of 46.6).

Radiocarbon ages

Plant macrofossils from 3.14, 2.82, 2.68 and 2.45 m in core EF10 were radiocarbon dated (Table 1). They were common salt-marsh plant species determined to be in growth position and with a known relationship to the former marsh surface. Three were *Spartina patens* and one was a rhizome and stem of *Scirpus* sp. Reported δ^{13}C values were consistent with these identifications (Chmura *et al.*, 1987). We also dated a horizontal fragment of wood at 3.27 m that was interpreted as having being deposited on a former marsh surface. These dates spanned the interval from 1806 to 1378 cal. a BP, with 2σ uncertainties for individual samples of ± 25 to ± 85 a.

Discussion

δ^{13}C values in salt-marsh plants and bulk surface sediments

A *Phragmites australis* (C_3) plant yielded δ^{13}C values of −25.2‰ and −24.6‰. This result is similar to δ^{13}C values (−29.4‰ to −24.6‰) reported for this species in other investigations (Chmura and Aharon, 1995; Cloern *et al.*, 2002). Measured δ^{13}C values (−14.0‰ and −13.8‰) from the *Spartina patens* plant (C_4) are within the range documented for

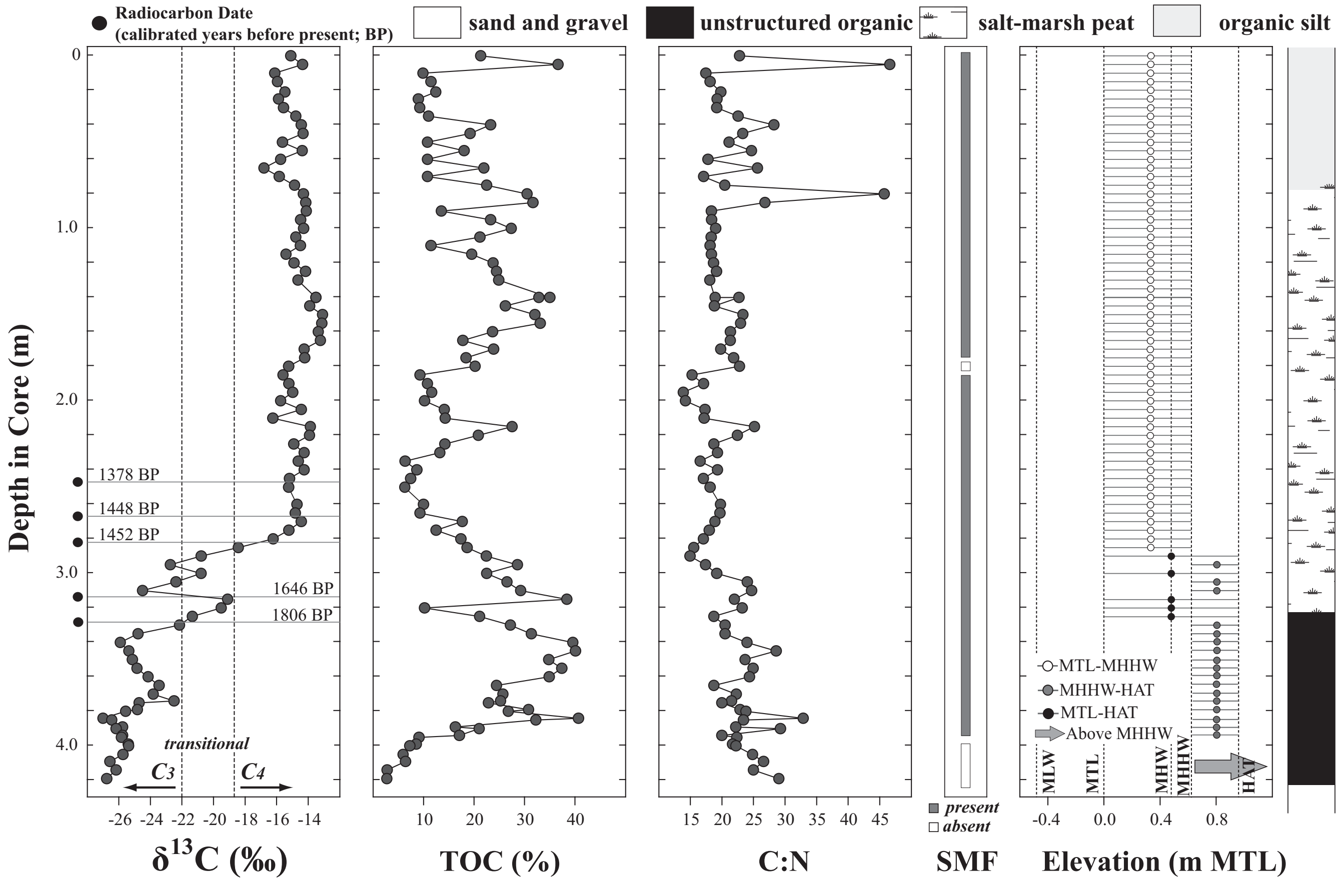

Figure 6. Measured values of δ^{13}C, total organic carbon (TOC) and C:N ratios in 91 samples from core EF10. Measurement errors (<0.1‰) are smaller than the symbols used. Vertical dashed lines differentiating C_3 and C_4 values are limits established from the four modern transects. Filled circles represent radiocarbon dates with mid-point ages. Presence of agglutinated foraminifera typical of salt-marshes (SMF) is shown by filled bars; open bars show absence of SMF (Kemp *et al.*, 2011). Elevation was estimated for samples with δ^{13}C values typical of C_4 salt-marsh plants as mean tide level (MTL) to mean higher high water (MHHW). Samples having δ^{13}C values associated with C_3 plants and the presence of agglutinated foraminifera were assigned an elevation from MHHW to highest astronomical tide (HAT). Samples having δ^{13}C values associated with C_3 plants and no salt-marsh foraminifera were assumed to have formed above MHHW (indicated by arrow). MLW, mean low water.

Table 1. Radiocarbon ages.

Depth (m)	^{14}C Age	δ^{13}C	Macrofossil	Max. BP	Min. BP	Lab code
3.27	1880 ± 30	−12.69	Horizontal woody fragment	1728	1884	OS-87528
3.14	1750 ± 30	−26.47	*Scirpus* sp.	1562	1731	OS-79178
2.82	1550 ± 25	−14.4	*Spartina patens*	1383	1521	OS-66514
2.68	1541 ± 14	−14.57	*Spartina patens*	1379	1517	OS-70445
2.45	1502 ± 14	−13.24	*Spartina patens*	1349	1407	OS-70443

Radiocarbon ages from core EF10. Ages at 2.68 and 2.45 m were derived from extended accelerator mass spectrometer counting to reduce analytical uncertainty and are not reported following rounding conventions. Maximum and minimum are calibrated ages (using Calib 6.0.2 with IntCal09) before present (BP). δ^{13}C was measured in a CO_2 aliquot collected during sample combustion and represents a value for the dated macrofossil and not the bulk sediment from which it was recovered. Radiocarbon ages were corrected for the effect of δ^{13}C fractionation by the reporting laboratory.

this species along the mid-Atlantic (Emery *et al.*, 1967) and northeast coasts of the USA (Middleburg *et al.*, 1997). Likewise, δ^{13}C values (−13.1‰ and −12.4‰) from *Spartina alterniflora* (C_4 plant) fell within reported ranges for this species (Ember *et al.*, 1987; Chmura and Aharon, 1995; Goñi and Thomas, 2000; Gebrehiwet *et al.*, 2008).

In New Jersey, bulk surface sediments from low- and high-marsh floral zones dominated by *Spartina alterniflora* (tall form) and *Spartina patens* or *Spartina alterniflora* (short form), respectively, yielded δ^{13}C values of −18.9‰ to −15.4‰ (Figs 2–4). These values are comparable to *Spartina* spp.-derived sediments along the Gulf and Atlantic coasts of the USA. In Louisiana, average δ^{13}C values for low-marsh *Spartina alterniflora* were −16.5‰ to −16.2‰ (DeLaune, 1986; Chmura *et al.*, 1987; Chmura and Aharon, 1995). In North Carolina, sediments under *Spartina alterniflora* were associated with δ^{13}C values of −18.6‰ to −14.0‰ (Craft *et al.*, 1988; Currin *et al.*, 1995; Kemp *et al.*, 2010). Similar sediments in South Carolina had δ^{13}C values of −20.1‰ to −15.4‰ (Ember *et al.*, 1987; Goñi and Thomas, 2000). In Georgia, values of −17.5‰ to −15.0‰ were measured (Fogel *et al.*, 1989). Middleburg *et al.* (1997) showed that *Spartina* spp. sediments had δ^{13}C values of −19.5‰ to −14.1‰ in Massachusetts.

Bulk sediment δ^{13}C values from the brackish transition zone (dominated by *Phragmites australis*, *Iva fructescens* and *Typha* sp.) in New Jersey were between −27.0‰ and −22.0‰ (Figs 2–4). Middleburg *et al.* (1997) reported a δ^{13}C value of −24.5‰ for bulk sediment at a salt-marsh upland border vegetated by *Phragmites australis*, *Typha* sp. and *Scirpus* sp. in Massachusetts. Bulk sediment δ^{13}C values from a salt-marsh to freshwater upland transition averaged −22.1‰ in Louisiana (Chmura *et al.*, 1987).

Four freshwater upland samples at Leeds Point had δ^{13}C values of −26.5‰ to −25.1‰ (Fig. 2). These values are within the range (−28.1‰ to −23.3‰) reported by similar studies. In Louisiana, freshwater marshes had an average δ^{13}C value of −27.8‰ (DeLaune, 1986; Chmura *et al.*, 1987), while forest sediments close to salt-marshes in South Carolina had δ^{13}C values of −28.8‰ to −27.5‰ (Goñi and Thomas, 2000). Bulk sediments fringing salt-marshes, but above astronomical tides, were associated with δ^{13}C values of −28.1‰ to −26.8‰ in North Carolina (Kemp *et al.*, 2010). In San Francisco Bay, freshwater sediments had δ^{13}C values of −27.2‰ to −23.3‰ (Cloern *et al.*, 2002).

Measured δ^{13}C values in bulk surface sediments from *Spartina alterniflora* and *Spartina patens* floral zones in New Jersey (−18.9‰ to −15.4‰) were less than in living plant tissue from the same species (−14.0‰ to −12.4‰). This pattern has been widely recognized (Haines, 1976; Ember *et al.*, 1987; Benner *et al.*, 1991). In North Carolina, *Spartina* sediments were up to 6.4‰ lower than corresponding plants (Craft *et al.*, 1988; Kemp *et al.*, 2010). Goñi and Thomas (2000) showed a difference of 4.0–6.8‰ in South Carolina. Bulk sediments in Georgia were up to 5.5‰ lower than *Spartina alterniflora* tissue (Fogel *et al.*, 1989; Benner *et al.*, 1991). Differences between δ^{13}C values from *Spartina* spp. tissue and sediment are a consequence of fractionation of carbon within living plants causing cellulose and lignin to have different δ^{13}C values (Lamb *et al.*, 2007). Following plant death, cellulose is decomposed by bacterial and fungal communities at a rate several times faster than lignin (Benner *et al.*, 1987, 1991; Buchan *et al.*, 2003), resulting in sediments with δ^{13}C values 4–7‰ lower than living *Spartina* spp. tissue (Ember *et al.*, 1987; Fogel *et al.*, 1989; Haddad *et al.*, 1992; Opsahl and Benner, 1995; Goñi and Thomas, 2000; Buchan *et al.*, 2003). Compound-specific measurements of δ^{13}C (e.g. on lignin only) can minimize the effect of diagenesis, although considerable additional sample preparation is necessary to extract the chosen compounds (Vane, 2003; Beramendi-Orosco *et al.*, 2004; Tanner *et al.*, 2007, 2010) that individually may only make small contribution to δ^{13}C in bulk sediment (e.g. lipids) and may not represent the dominant plant community. Bulk sediment includes allochthonous material that can enhance or dampen diagenetic effects depending on its source (Lamb *et al.*, 2006). Low-marsh sites receive inputs of marine algae with δ^{13}C values of approximately −25‰ to −16‰ (Lamb *et al.*, 2006). In sufficient quantities inputs of marine algae could enhance the influence of diagenesis of *Spartina* spp. sediment. In Georgia, Gebrehiwet *et al.* (2008) concluded that 75% of organic material in salt-marsh sediment was derived from phytoplankton based on a mixing model with a δ^{13}C value for marine algae of −19.8‰. In contrast, Chmura and Aharon (1995) concluded that plants in growth position were the dominant source of organic material in bulk surface sediment.

Fractionation of carbon during early diagenesis was not discernible (within measured ranges) between *Phragmites australis* plant tissue (−25.2‰ to −24.6‰) and bulk sediment (−27.0‰ to −22.0‰). Field and laboratory experiments have shown that δ^{13}C values from *Phragmites australis* tissue underwent change of less than 2‰ during early decomposition (Balogh *et al.*, 2006), which is less than the reported range for living examples. Bulk sediment from transitional *Phragmites australis* zones is more likely to receive allocthonous inputs from nearby freshwater uplands than material with a marine isotopic signature from tidal inundation. This process could offset or mask diagenetic effects, although laboratory experiments without allocthonous inputs suggest otherwise.

Beyond the period of initial decomposition, several investigations have shown that bulk sediment δ^{13}C values are incorporated into coastal sediments in a manner allowing reliable identification of floral zones after more than 3000 a (Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004; Lamb *et al.*, 2007). These studies suggested that fractionation of bulk sediment δ^{13}C is most pronounced shortly after deposition of dead plant material and that bulk sediment underwent little further change. In core EF10, consistency of δ^{13}C values from 0.05 to 2.80 m (−14.8‰ ± 0.8‰; 1σ) suggests that no systematic, post-depositional shift can be discerned in bulk sediments derived from C_4 plants, corresponding to approximately 1450 a (Fig. 6). This interpretation assumes that there was no long-term change in sediment source to systematically offset diagenetic change over the same period.

In southern New Jersey, C:N values measured in living examples of *Spartina alterniflora*, *Spartina patens* and *Phragmites australis* were less than those in bulk sediment from equivalent floral zones (Fig. 5A). The tendency for C:N values from upland, high-marsh and low-marsh environments to converge on similar values was shown by Goñi and Thomas (2000) in South Carolina and Kemp *et al.* (2010) in North Carolina. This could be a consequence of diagenesis that retains immobile nitrogen while carbon is lost through oxidation (Chmura *et al.*, 1987; Ember *et al.*, 1987). Alternatively, it may reflect allochthonous input of algae, particulate or dissolved organic carbon with C:N that is commonly less than 10 (Cifuentes, 1991; Lamb *et al.*, 2006).

Reconstructing Holocene relative sea-level changes

Salt-marsh plants form elevational zones because of their differing tolerances to frequency and duration of saline inundation (Chapman, 1960; Redfield, 1972; Niering and Warren, 1980). This distinctive pattern provides a means to reconstruct RSL by recognition of floral communities in coastal sedimentary archives (Shennan, 1986; Tornqvist *et al.*, 2004, 2006; Johnson *et al.*, 2007). Reconstructing RSL requires that the elevational range of each floral zone be robustly estimated from modern salt-marshes. There are ecological circumstances where the distribution of dominant plant species is distorted from the prevailing regional pattern controlled by tidal inundation. For example, *Phragmites australis* is able to extend its distribution below MHHW in response to enhanced availability of nitrogen (Minchinton and Bertness, 2003) or disturbance of nearby high-marsh communities (Minchinton, 2002). Studies of *Spartina alterniflora* have documented its expansion to higher elevations under low light conditions (Vasilas *et al.*, 2011). Therefore switches in plant community (and associated δ^{13}C values) can occur independently of changing tidal inundation. Consistency of plant distributions and δ^{13}C values among and within the New Jersey sites (including measured boundaries between plant communities at Leeds Point) suggests that these occurrences are likely localized and transient. Describing the modern distribution of salt-marsh plants at multiple sites with different characteristics serves to include ecologically unusual occurrences. Indicative meanings reflect the typical range for plant species rather than maximum possible extent (Table 2). In the sedimentary record, short-lived changes (several years) are rarely preserved because of the time-averaging effect of bulk sediment samples. Stratigraphically ordered samples from a core and multiple cores minimize the influence of these factors.

While there is no correlation between elevation and measured δ^{13}C values (Fig. 5B; Kemp *et al.*, 2010), recognition of floral zones in an appropriate stratigraphical context allows RSL to be reconstructed. To consider bulk sediment δ^{13}C values as a sea-level indicator in southern New Jersey we estimated the indicative meaning of 91 samples from core EF10. These estimates and interpretations assume that plant species have maintained their ecological preferences and physiology throughout the period under consideration, including the present. Furthermore, it must be assumed that the same floral communities were present for the period of interest.

One of four indicative meanings was assigned to samples in core EF 10 (Table 2 and Fig. 6):

1. δ^{13}C values greater than −18.9‰ formed between MTL and MHHW.

   Measured δ^{13}C in modern bulk sediment did not distinguish low- and high-marsh floral zones dominated by C_4 plants (Fig. 5). Sediment δ^{13}C values from these environments in New Jersey were −18.9‰ to −15.4‰. We recognized a salt-marsh environment as having δ^{13}C values greater than −18.9‰ and occupying an elevational range from MTL to MHHW, which are the lower and upper tidal limits of vegetated modern salt-marshes in the study region. Under current tidal conditions at Leeds Point, this range is 0.59 m.
2. δ^{13}C values less than −22.0‰ and lacking agglutinated foraminifera formed above MHHW.

   Brackish (−27.0‰ to −22.0‰) and freshwater upland (−26.5‰ to −25.1‰) environments dominated by C_3 plants could not be separated using δ^{13}C values (Fig. 5). Core samples having δ^{13}C values associated with C_3 plants (less than −22.0‰) were interpreted as having formed above MHHW. Such samples should be restricted to establishing freshwater limiting points, which constrain only the upper altitude of former RSL (Shennan and Horton, 2002; Engelhart *et al.*, 2009, 2011b).
3. δ^{13}C values less than −22.0‰ with agglutinated foraminifera formed between MHHW and HAT.

   In southern New Jersey, foraminifera are absent in modern freshwater upland sediments, while modern brackish sediments include agglutinated taxa (Kemp *et al.*, 2011). Samples with δ^{13}C values less than −22.0‰ and presence of agglutinated foraminifera were interpreted as having formed between MHHW and HAT. Under current tidal conditions at Leeds Point this range is 0.31 m.
4. Intermediate δ^{13}C values (−22.0‰ to −18.9‰) with agglutinated foraminifera formed between MTL and HAT.

Table 2. Indicative meanings.

Floral zone	Dominant vegetation	Elevational range	δ^{13}C (‰)
Low salt-marsh	*Spartina alterniflora* (tall form)	MTL to MHW	>−18.9
High salt-marsh	*Spartina patens* *Spartina alterniflora* (short form)	MHW to MHHW	>−18.9
Brackish transition	*Phragmites australis* *Typha* sp. *Iva fructescens*	MHHW to HAT[a] Above MHHW[b]	<−22.0

Indicative meanings assigned to salt-marsh floral zones. These values provided estimates of paleomarsh elevation for samples in core EF10. MSL, mean sea level; MHW, mean high water; MHHW, mean higher high water; HAT, highest astronomical tide. For the brackish transition zone, we used two different ranges depending on the presence ([a]) or absence ([b]) of agglutinated foraminifera that are not present in modern freshwater upland environments.

> The floral community represented by samples with intermediate $\delta^{13}C$ values is equivocal, although presence of agglutinated foraminifera indicates an intertidal origin. Such samples were assigned an indicative range from MTL to HAT reflecting this uncertainty and corresponding to a 0.90 m range at Leeds Point today.

Samples from core EF10 below 3.95 m had $\delta^{13}C$ values of −26.8‰ to −25.4‰. Foraminifera were absent in these samples; therefore we interpreted them as having formed above MHHW. Between 3.95 and 2.80 m, 29 samples had $\delta^{13}C$ values from −27.0‰ to −16.2‰ and presence of agglutinated foraminifera. Of these, 24 had $\delta^{13}C$ values less than −22.0‰ and were assigned an elevational range from MHHW to HAT. Five samples had intermediate $\delta^{13}C$ values and were assigned a range of MTL to HAT. Measured $\delta^{13}C$ values in 58 samples in the upper 2.80 m of core EF10 ranged from −18.4‰ to −13.1‰. These values are within the range of modern sediments from vegetated salt-marshes in southern New Jersey and we assigned these samples a range of MTL to MHHW. The sample at 1.8 m ($\delta^{13}C$ value of −15.2‰) provides a unique example (in this core) of how $\delta^{13}C$ values can be applied in RSL reconstructions. A bulk sediment $\delta^{13}C$ measurement greater than −18.9‰ allowed this sample to be classified as having a salt-marsh origin typical of New Jersey despite absence of foraminifera.

Bulk sediment $\delta^{13}C$ values synonymous with C_4 plants can reconstruct RSL where the sedimentary context of a sample and modern transects support an interpretation of a salt-marsh origin. This scenario is applicable to the northeast and mid-Atlantic coasts of the USA, where C_4 plants are (and have been) the dominant plant species on salt-marshes (van de Plassche, 1991; Gehrels, 1994; Middleburg *et al.*, 1997). The elevational range corresponding to MTL–MHHW varies among regions due to differences in tidal range, making the precision of this approach geographically variable. Threshold $\delta^{13}C$ values for distinguishing floral samples require an appropriate modern dataset and were less than 2‰ among the modern sites we documented.

Understanding changes in plant community and RSL using samples with $\delta^{13}C$ values typical of C_3 plants is made difficult by the inability to distinguish freshwater environments that are not restricted to tidal limits from brackish floral environments in the uppermost part of the tidal frame. Caution dictates that such samples be treated as freshwater limiting points. However, presence of agglutinated foraminifera can distinguish these environments. The combination of a C_3 $\delta^{13}C$ value and presence of agglutinated foraminifera in New Jersey is restricted to the interval from MHHW to HAT and is the most precise of the four interpretations we recognized. Determining presence or absence of agglutinated foraminifera can be done quickly, cheaply and with minimal taxonomic training.

In contrast to New Jersey, high-salt-marsh floral zones along the southeastern Atlantic and Gulf of Mexico coasts are often dominated by the C_3 plant *Juncus roemerianus* (Eleuterius, 1976). Although C_4 plants do exist in the high marsh, their dominance is frequently restricted to low-marsh floral zones (Chmura *et al.*, 1987; Kemp *et al.*, 2010). The difficulties of paleoenvironmental interpretation in this region were recognized by Chmura and Aharon (1995) and described with specific reference to RSL reconstruction by Kemp *et al.* (2010). In such settings fresh, brackish and high-salt-marsh floral zones cannot be distinguished using $\delta^{13}C$ values. Indicative meanings from New Jersey are therefore not applicable in regions with different salt-marsh biomes or to buried sediments that formed in these circumstances. The current geographic division between these ecological regions on the Atlantic coast of the USA is shown by sharp contrasts in the distribution of *Juncus roemerianus,* which covers 49–77% of salt-marsh area in North Carolina, less than 10% in Virginia and Maryland, and less than 0.1% in Delaware and states farther north (Eleuterius, 1976).

Salt-marsh development at Leeds Point

The combination of $\delta^{13}C$ values and presence of agglutinated foraminifera in core EF10 provides insight into salt-marsh development at Leeds Point. Measured $\delta^{13}C$ values from 3.2 m to 2.8 m displayed clear variability (−24.5‰ to −16.4‰) and were frequently transitional between C_3 and C_4 values (−22.0‰ to −18.9‰; Fig. 6). This period of variability may represent encroachment of a salt-marsh floral community on a brackish transitional zone. Radiocarbon dates show that the change took approximately 350 years (1806 cal. a BP at 3.27 m to 1452 cal. a BP at 2.82 m; Fig. 6) to be manifest in measured $\delta^{13}C$ values, although measurement and calibration uncertainties can accommodate 207–501 years. A study focused on salt-marsh evolution in North Carolina concluded that it would take more than 200 years for bulk sediment along the border of a freshwater upland to develop the characteristics of a *Spartina patens* high marsh, even though the plant community was able to establish itself in 3–5 years (Craft *et al.*, 2002). The trajectories of such developments are likely to be nonlinear and affected by other changes during that time, such as climate variability (Craft *et al.*, 2002). Models of salt-marsh response to sea-level change predict a lag time of several decades (Kirwan and Murray, 2008). For the 350-year period of change in EF10 it is not possible to distinguish between time taken for the dominant plant species to change and time taken for bulk sediment to subsequently reflect this botanical change.

Conclusions

We investigated the use of $\delta^{13}C$ values from bulk organic sediment to reconstruct the botanical origin of samples from coastal sediments in New Jersey, USA, as a proxy for tidal elevation. Modern transects at three sites showed that sediment derived from C_4 plants had $\delta^{13}C$ values from −18.9‰ to −15.8‰ and included a low-salt-marsh floral zone vegetated by *Spartina alterniflora* (tall form) and a high-salt-marsh community dominated by *Spartina patens* and *Spartina alterniflora* (short form). Bulk sediment associated with C_3 plants had $\delta^{13}C$ values of −27.0‰ to −22.0‰. These environments included brackish transitional zones vegetated by *Phragmites australis* with *Iva Fructescens* and freshwater upland. A replicate modern transect at one site demonstrated no discernible intra-site variability among samples from the same floral zone. Comparison of sediment $\delta^{13}C$ values with examples of living plants from the study sites showed that *Spartina* spp. underwent diagenetic change shortly after deposition (up to 6.5‰), but then likely remained unchanged for at least 1500 years. Changes to *Phragmites australis* were less than 2‰. We used 91 samples from a core collected at Leeds Point to investigate the use of $\delta^{13}C$ values for establishing the botanical origin of sediments. Four classifications of samples were proposed which demonstrate the advantage of a multi-proxy sea-level indicator combining $\delta^{13}C$ values with presence or absence of agglutinated foraminifera:

1. Samples with $\delta^{13}C$ values greater than −18.9‰ formed on a vegetated salt-marsh between MTL and HAT. Such an interpretation remains valid in the absence of foraminifera.
2. Sediment with $\delta^{13}C$ values less than −22.0‰ and containing agglutinated foraminifera formed in a brackish transitional zone between MHHW and HAT. This classification

had the narrowest elevational range and is therefore the most precise sea-level indicator.

3. Sediment with $\delta^{13}C$ values less than −22.0‰ and lacking foraminifera may be unrelated to former sea level and is interpreted as having formed above MHHW. Inability of $\delta^{13}C$ values to distinguish brackish and freshwater-derived sediments is its primary limitation in New Jersey and similar regions.
4. Samples with intermediate $\delta^{13}C$ values (−22.0‰ to −18.9‰) are interpreted as having formed between MTL and HAT, reflecting uncertainty in determining floral origin.

Core EF10 records the change from brackish transitional community to a salt-marsh. A 0.4 m thick section spans the change between these two environments and is typified by intermediate $\delta^{13}C$ values. Radiocarbon dating suggests that this change took place between 1807 and 1452 cal. a BP. This period is broadly similar to empirical predictions of the time needed for bulk organic sediment at the border of a freshwater upland to assume the characteristics of a C_4 dominated salt-marsh.

Supporting information

Additional supporting information can be found in the online version of this article:

Table S1 New Jersey modern bulk sediments.

Please note: This supporting information is supplied by the authors, and may be re-organized for online delivery, but is not copy-edited or typeset by Wiley-Blackwell. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

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Abbreviations. HAT, highest astronomical tide; MHHW, mean higher high water; MHW, mean high water; MLLW, mean lower low water; MTL, mean tide level; PDB, Pee Dee Belemnite; RSL, relative sea level; RTK, real time kinematic; SWLI, standardized water-level index; TOC, total organic carbon; VPDB, Vienna Pee Dee Belemnite.

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