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

Andrew C. Kemp[ab*], Christopher H. Vane[c], Benjamin P. Horton[d], Simon E. Engelhart[d], and Daria Nikitina[e]

[a] *School of Forestry and Environmental Studies, Yale University, New Haven, CT 06510, USA.*

[b] *Yale Climate and Energy Institute, Yale University, New Haven, CT 06510, USA.*

[c] *British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, UK.*

[d] *Sea Level Research, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA 19104, USA.*

[e] *Department of Geology and Astronomy, West Chester University, West Chester, PA 19380, USA.*

* *Corresponding author, andrew.kemp@yale.edu; tel 203 436 3978*

Abstract

We investigated use of $\delta^{13}C$ values in bulk organic sediment to reconstruct the botanical origin of samples preserved in coastal sedimentary archives as a proxy for 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 at elevations 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 presence or absence of agglutinated foraminifera to recognize four sample types. Sediment less depleted than -18.9‰ was derived from a vegetated salt marsh and formed between MTL and MHHW. Sediment more depleted than -22.0‰ and containing agglutinated foraminifera formed in a brackish transitional zone between MHHW and HAT. Sediment more depleted than -22.0‰ and lacking foraminifera formed above MHHW and maybe unrelated to former sea level. Samples with intermediate values (-22.0‰ to -18.9‰) formed between MTL and HAT. Radiocarbon dates suggest that a transition from brackish to salt marsh $\delta^{13}C$ values recorded in the core took approximately 350 years (1807-1452 years BP).

Keywords

Stable carbon isotope, salt marsh, New Jersey, sea level, Spartina

1 Introduction

Stable carbon isotopes have been used to determine the botanical and environmental origin of organic material preserved in coastal sedimentary archives (Chmura and Aharon, 1995; 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, which 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). $\delta^{13}C$ values are the ^{13}C:^{12}C ratio measured in samples and expressed in parts per mil (‰) compared to a standard reference sample (Pee Dee Belemnite, PDB). During photosynthesis, land plants preferentially concentrate the ^{12}C isotope to varying degrees; this fractionation of atmospheric carbon is recorded in plant tissues. 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). In contrast, freshwater uplands from elevations above the uppermost limit of tidal inundation are associated with plants using the C_3 pathway (Middleburg *et al.*, 1997; Lamb *et al.*, 2006). As the dominant input to salt-marsh sediments is likely derived from vascular vegetation (Malamud-Roam and Ingram, 2001; Lamb *et al.*, 2006), bulk sediment $\delta^{13}C$ values can be used as a proxy for describing the dominant vegetation at the time of deposition (Malamud-Roam and Ingram, 2004). However, measurements of $\delta^{13}C$ in bulk sediment also include allochthonous material that may be derived from fresh, brackish or marine environments as either dissolved or particulate matter (Lamb *et al.*, 2006; Gebrehiwet *et al.*, 2008). Further difficulties arise from the presence of 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 distinguish between 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 in study areas where C_3 and C_4 plants have existed (with different distributions) over the period under consideration (Wilson *et al.*, 2005a) and requires an understanding of the influence of post-depositional diagenesis on measured $\delta^{13}C$ values (DeLaune, 1986; Ember *et al.*, 1987; Fogel *et al.*, 1989). The precision of this approach may be increased if salt marshes can be 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 (Edwards, 2007). 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 types they represent) and elevation in the tidal frame (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 the use of $\delta^{13}C$ values from bulk-organic sediments to identify salt-marsh floral zones and be used as sea-level indicators in southern New Jersey, USA. The $\delta^{13}C$ values of modern (surface) bulk sediments and plants were measured in samples collected along salt-marsh transects reflecting an environmental and elevational gradient at three study sites (Figure 1). Replicate transects at one site (Leeds Point) facilitates investigation of intra-site variability. We use this modern dataset in tandem with foraminiferal data (Kemp et al.) to interpret $\delta^{13}C$ values measured in a 4.4 m core of organic sediment 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. Preliminary results from radiocarbon dating estimate the timing and duration of a change in dominant plant community preserved in the core (1807 to 1452 years BP).

2 Study Area

The central and southern Atlantic coast of New Jersey is characterized by a chain of barrier islands, separating a back-barrier lagoon system from the open ocean. The coast between Great Bay to the north and Cape May to the south (Figure 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 vertical accretion of salt-marsh sediment (Daddario, 1961; Meyerson, 1972; Thorbjarnarson *et* *al.*, 1985; Psuty, 1986; Ferland, 1990). The resulting sequences of sediment provide archives of Holocene sea-level and environmental change.

Modern salt marshes in this region form extensive platforms. Tidal flats are rare as the coast is experiencing ongoing 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 floral zones are characterized by *Spartina patens*, *Spartina alterniflora* (short form) and *Distichlis spicata* (Daddario, 1961). The border between salt marshes and freshwater upland is vegetated by *Phragmites australis* and *Iva fructescens,*with less frequent occurrences of *Typha* sp. and *Scirpus* sp. This zone is typically narrow and represents brackish conditions (Daddario, 1961; Stuckey and Gould, 2000).

The region has a semidiurnal tidal cycle and is microtidal. Tidal ranges (MLLW to MHHW) are slightly larger on the ocean side of the barrier islands (1.4 m at Atlantic City; Figure 1) than in the lagoons. Tidal ranges at the study sites around Great Bay were estimated by VDatum (Yang *et al.*, 2008) to be 1.1 m at Leeds point and Bass River and 1.3 m at Brigantine Barrier.

The three sites described in this study were also the focus of an investigation into the modern distribution of salt-marsh foraminifera (Kemp et al.). Leeds Point is situated on the west side of Great Bay (Figure 1). Salt-marshes in this area frequently exceed 1 km in width (Ferland, 1990). We sampled two transects (A-A' and B-B'; Figures 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 dominated by *Spartina patens* associated 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 the Leeds Point site in a high salt marsh environment (Figure 1).

We established a 50 m long transect (C-C') at the confluence of Bass River with Great Bay (Figure 1). The transect ran from a brackish, transitional (salt-marsh to upland) zone defined by *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 floral zone of tall-form *Spartina alterniflora* (Figures 1b and 3a).

The site at Brigantine Barrier is a back-barrier salt marsh (Figure 1). 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 floral zone defined by *Spartina patens* and *Spartina alterniflora* (short form) and a low-marsh floral zone of patchy *Spartina alterniflora* (tall form) and exposed muddy sediment (Figures 1c and 4a).

3 Methods

3.1 Sampling Regime

At the three sites we established transects across the modern salt marsh, which were positioned to include the full range of physiographic environments at each site (Figure 1). Sampling stations reflected changes in elevation and vascular vegetation. At each station we collected bulk surface (0-1 cm) sediment for analysis. 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 and VDatum was used to convert altitudes from orthometric to tidal datums. We collected examples (leaf and stem) of living salt-marsh plants (*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 type of vegetation.

A core (EF10) was selected for analysis from the Leeds Point site following stratigraphic investigation. The core was recovered in 50 cm sections using a Russian-type hand core. It was sampled at a resolution of 5 cm in the laboratory to ensure that all stratigraphic units were adequately represented. Each core sample consisted of a 1 cm thick section of sediment.

3.2 Stable carbon isotopes preparation and measurement

Modern and core bulk sediment samples were prepared for measurement of $\delta^{13}C$, C:N and Total Organic Carbon (TOC) by treatment with 5% HCL for 18 hours. They were then washed with deionized water. Plant samples were washed with deionized water to remove sediment particles. All sample types were dried overnight in an oven at 40ºC and milled to a fine powder using a pestle and mortar. ^{13}C:^{12}C and TOC analyses were performed by combustion in a Costech Elemental Analyzer coupled on-line to a Optima dual-inlet mass spectrometer, with $\delta^{13}C$ values calculated to the Vienna Pee Dee Belemnite (VPDB) scale using a within-run laboratory standard (cellulose, Sigma Chemical prod. no. C-6413) calibrated against NBS-19 and NBS-22. C:N ratios were analyzed on the same instrument and 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 a precision of ± <0.1‰ for $\delta^{13}C$ (1σ). For measurements of nitrogen, the precision was ± 0.16 (1σ).

3.3 Radiocarbon ages

Radiocarbon ages were obtained for five samples from core EF10. The selected samples were identifiable macrofossils of common salt-marsh species that were determined to be in growth position and had a known relationship to the former marsh surface. In addition a woody fragment lying horizontally in the core was interpreted as having been deposited on a former marsh surface. Each sample was cleaned under a microscope to remove contaminating material such as adhered sediment or invasive younger roots and dried at <50ºC. 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).

4 Results

4.1 Characterization of modern salt-marsh sediments and plants

The δ^{13}C, C:N and TOC composition of modern salt-marsh sediments was measured in 61 surface (0-1 cm) samples collected at the three study sites. Along Leeds Point transect A (Figure 2, left panels, A-D), samples between 0 and 22 m (stations 1 to 5) had δ^{13}C values from -27.0‰ to -22.7‰, TOC of 4% to 32% and C:N ratios of 12.4 to 14.4. These samples were associated with freshwater upland and *Phragmites australis* with *Iva fructescens* environments. Samples from 30-108 m along the transect in areas vegetated by *Spartina patens* and *Spartina alterniflora* recorded δ^{13}C values from -17.5‰ to -15.8‰, TOC between 7.5 and 23.6% and measured C:N ratios from 12.1 to 16.6 (Figure 2).

A similar pattern was observed on the second transect from Leeds Point (Figure 2, right panels, E-H). Samples between 0 and 25 m (stations 1 to 8) had δ^{13}C values from -26.7‰ to -22.9‰, TOC of 3-32% and C:N ratios of 12.9 to 15.3. These samples were associated with freshwater upland and *Phragmites australis* with *Iva fructescens* environments. Between 34 and 81 m (stations 9 to 18), δ^{13}C values measured in 10 samples from *Spartina patens*, *Spartina alterniflora* and unvegetated muddy zones varied from -18.7‰ to -16.2‰ with TOC values of 7-24% and C:N ratios of 12.6-17.3.

At Bass River (Figure 3), a single sample (station 1) situated in a stand of *Phragmites australis* had a δ^{13}C value of -25.0‰, TOC of 2.6% and C:N ratio of 14.6. Samples collected from *Spartina patens*, *Spartina alterniflora* and muddy unvegetated sediment zones had measured $\delta^{13}C$ values of -20.5‰ to -15.4‰, TOC values of 0-33% and C:N ratios of 8.8 to 22.4 (Figure 3).

The transect at Brigantine Barrier included a single sample (station 1) situated in a stand of mixed stand of *Phragmites australis* and *Iva fructescens* which had a $\delta^{13}C$ value of -22.0‰, TOC of 26.2% and C:N ratio of 13.8 (Figure 4). Stations 2-12 were situated in a mixed zone of *Spartina patens*, *Spartina alterniflora* and *Salicornia* spp. These samples had $\delta^{13}C$ values of -18.9‰ to -16.1‰, measured TOC of 1% to 38% and C:N ratios between 10.5 and 15.5. Three samples collected from unvegetated muddy sediment at 115-117 m (stations 13-15) had $\delta^{13}C$ values of -18.5‰ to -16.5‰, measured TOC of 5% to 10% and C:N ratios between 9.5 and 14.1 (Figure 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 (Figure 1). 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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.

4.2 Characteristics of bulk sediments in core EF10

We measured δ^{13}C, TOC and C:N in 91 samples (1 cm thick) of sediment recovered from the upper 4.2 m of core EF10 which represents the sedimentary units above the basal sand (Figure 6). δ^{13}C values from the lowermost section of the core (4.20 m to 3.35 m depth) varied from -26.8‰ to -22.2‰. Between 3.35 m and 2.80 m there was a trend toward less depleted δ^{13}C values (Figure 6), ten samples in this interval varied from -24.8‰ to -19.1‰. There was relatively little variability in δ^{13}C from the upper 2.80 m of the core, where measured values varied from -16.2‰ to -13.1‰. Measured TOC between 4.20 m and 3.40 m in the core increased from 3% to 39.5% (Figure 6). A reversal of this trend was observed between 3.40 m and 2.40 m with measured TOC values that decreased from 39.5% to 8.6%. In the upper part of the core (top 2.40 m), TOC increased to a peak of 32.8% at 1.40 m (Figure 6) and averaged 18.3%. There was no clear trend in measured C:N ratios from core EF10 (Figure 6), which varied from 13.8 to 32.8 (average 20.9), with the exception of two anomalous data points at depths of 0.80 m (C:N of 45.7) and 0.05 m (C:N of 46.6).

4.3 Radiocarbon ages

Four plant macrofossils from depths of 3.14 m, 2.82 m, 2.68 m and 2.45m in core EF10 were radiocarbon dated (Table 1). Three of the samples were identified as *Spartina patens* and yielded δ^{13}C values consistent with this interpretation (Chmura *et al.*, 1987). One macrofossil was a rhizome and of *Scirpus* sp. We also dated a horizontal fragment of wood at 3.27 m. After calibration these dates spanned the interval from 1806 to 1378 years BP with 2σ uncertainty from ±25 to ±85 years.

5 Discussion

5.1 Modern distribution of salt-marsh plants

Salt-marsh plant communities form elevation-dependent floral zones because of their differing tolerances to frequency and duration of inundation by saline water (Chapman, 1960; Redfield, 1972; Niering and Warren, 1980). This distinctive pattern provides a means to reconstruct relative sea level by recognition of these floral zones in coastal sedimentary archives where organic material has accumulated, such as salt marshes, infilled lagoons and estuaries (Shennan, 1986). To do so, requires that the elevational range of each floral zone can be robustly estimated from modern salt marshes. In southern New Jersey, we recognized three salt-marsh floral zones which are present at each of the study sites. These zones were assigned a conservative (broad elevational range to capture ecologically rare occurrences) indicative meaning (Table 2), similar to those established by van de Plassche (1991) in Connecticut, USA. The narrow zone of *Phragmites australis* (often with *Typha* sp. and *Iva fructescens*) between freshwater upland and salt-marsh environments was given an indicative meaning of having formed above mean higher high water (MHHW). No upper limit was established for this plant 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 dominated by *Spartina patens*, *Distichlis spicata* and stunted *Spartina alterniflora* were associated with elevations between MHW and MHHW (Table 2). Measurements of the modern boundary between high-marsh and brackish transitional floral zones at the Leeds Point site (*n*=88) located it within 2 cm of MHHW.

Low-marsh floral zones characterized by *Spartina alterniflora* (tall form) were assigned an indicative meaning of mean tide level (MTL) to MHW. At Leeds Point, 70 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 ±1σ confidence interval of 6 cm.

The modern distribution of salt-marsh foraminifera was described at the same three study sites by Kemp et al. (in review), who recognized five distinct assemblages. In freshwater upland environments, foraminifera were absent in surface sediments. Foraminifera require brackish, saline or marine conditions and are not found in sediments from freshwater upland environments 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 alternatively Jadammina macrescens* with *Trochammina inflata*. High-marsh floral environments were dominated by *Arenoparrella mexicana* and *Tiphotrocha comprimata*. The low-marsh floral zone was uniformly dominated by *Miliammina fusca*.

5.2 Salt-marsh plant $\delta^{13}C$ values

The physiological contrast between C_3 and C_4 photosynthetic pathways is reflected in $\delta^{13}C$ values measured in living salt-marsh plants (Chmura and Aharon, 1995). Isotopic differences arise from discrimination against $^{13}CO_2$ by the Rubisco enzyme in favor of $^{12}CO_2$. The net effect of this process is smaller in plant species producing 4-carbon sugars (C_4) resulting in less depleted $\delta^{13}C$ values (modal value -12‰) than in those producing 3-carbon sugars (C_3), which have an average $\delta^{13}C$ value of -27‰ (Schlesinger, 1997; Choi *et al.*, 2001; Fry, 2006). In this study, an example of *Phragmites australis* (C_3 plant) yielded $\delta^{13}C$ values of -25.2‰ and -24.6‰. This result is directly to comparable to other investigations, which have reported similar $\delta^{13}C$ values (-29.4‰ to -24.6‰) for this species (Chmura and Aharon, 1995; Cloern *et al.*, 2002). The $\delta^{13}C$ values from *Spartina patens* (C_4 plant) in southern New Jersey (-14.0‰ and -13.8‰) are within the range documented for this species in published studies along the mid-Atlantic (Emery *et al.*, 1967) and north east coasts of the USA (Middleburg *et al.*, 1997). Likewise, measured $\delta^{13}C$ values from an example of *Spartina alterniflora* (C_4 plant) in this study (-13.1‰ and -12.4‰) fell within reported ranges for the species (Ember *et al.*, 1987; Chmura and Aharon, 1995; Goñi and Thomas, 2000; Gebrehiwet *et al.*, 2008).

5.3 $\delta^{13}C$ values in bulk surface sediments

In New Jersey, bulk surface sediments from low and high-marsh floral zones dominated by *Spartina alterniflora* (tall form) and *Spartina patens* respectively, yielded $\delta^{13}C$ values of -18.9‰ to -15.4‰ (Figures 2 to 4). These values are comparable to those found along the Gulf and Atlantic coasts of the USA for *Spartina* spp.-derived sediments. In Louisiana, average $\delta^{13}C$ values of -16.5‰ to -16.2‰ were reported for low marsh *Spartina alterniflora* (DeLaune, 1986; Chmura *et al.*, 1987; Chmura and Aharon, 1995). In North Carolina, sediments under *Spartina alterniflora* have been associated with $\delta^{13}C$ values of between -18.6‰ and -14.0‰ (Craft *et al.*, 1988; Currin *et al.*, 1995; Kemp *et al.*, 2010). Similar sediments in South Carolina had $\delta^{13}C$ 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* 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‰ (Figures 2 to 4). Middleburg et al. (1997) reported a δ^{13}C value of -24.5‰ for bulk sediment at the upland border of salt marshes vegetated by *Phragmites australis*, *Typha* sp. and *Scirpus* sp. in Massachusetts. Whilst these species of vegetation are less common in other regions, bulk sediment δ^{13}C values from the transition between freshwater upland and salt marsh had an average value of -22.1‰ in Louisiana (Chmura *et al.*, 1987).

Four bulk sediment samples from the freshwater upland at Leeds Point had δ^{13}C values of -26.5‰ to -25.1‰ (Figure 2). These values are similar to those reported for freshwater upland sediments in other studies that varied from -28.1‰ to -23.3‰. In Louisiana, an average δ^{13}C value of -27.8‰ was provided for freshwater marshes (DeLaune, 1986; Chmura *et al.*, 1987), whilst 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 above the influence of astronomical tides were associated with δ^{13}C values of -28.1‰ to -26.8‰ in North Carolina (Kemp *et al.*, 2010). In the San Francisco Bay estuarine system, freshwater sediments were shown to have δ^{13}C values of -27.2‰ to -23.3‰ (Cloern *et* *al.*, 2002). Upland border sediments in Massachusetts were reported as having a $\delta^{13}C$ value of -24.5‰ (Middleburg *et al.*, 1997).

The range of $\delta^{13}C$ values reported for bulk surface sediments from *Spartina alterniflora* and *Spartina patens* floral zones in New Jersey (-18.9‰ to -15.4‰) was more depleted than living plant tissue (stems and leaves) from the same species (-14.0‰ to -12.4‰). A consistent depletion of bulk sediment $\delta^{13}C$ compared to *Spartina* spp. tissues has been widely recognized (Haines, 1976; Ember *et al.*, 1987; Benner *et al.*, 1991). In North Carolina, *Spartina* sediments up to 6.4‰ more depleted than corresponding plants have been reported (Craft *et al.*, 1988; Kemp *et al.*, 2010). Similarly, Goni and Thomas (2000) showed a difference of 4.0‰ to 6.8‰ in South Carolina. Bulk sediments up to 5.5‰ more depleted than *Spartina alterniflora* tissue were recorded in Georgia (Fogel *et al.*, 1989; Benner *et al.*, 1991). Differences between $\delta^{13}C$ values from *Spartina* tissue and sediment are a consequence of fractionation of carbon within plant tissues causing cellulose and lignin from the same living plant to have different $\delta^{13}C$ values (Lamb *et al.*, 2007). During early diagenesis following the plant's death, cellulose is decomposed by bacterial and fungal communities at a rate several times faster than lignin (Benner *et al.*, 1987; Benner *et al.*, 1991; Buchan *et al.*, 2003), resulting in sediments 4‰ to 7‰ more depleted 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). In addition, bulk sediments include allochthonous material that can enhance or dampen diagenetic differences to living plant material depending on its source (Lamb *et al.*, 2006).

In contrast to *Spartina* spp., further 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 on *Phragmites australis* have shown that $\delta^{13}C$ values from *Phragmites australis* tissue underwent a change of less than 2‰ during early decomposition (Katalin *et al.*, 2006), which is less than the range reported for living examples of this species. Beyond the period of initial decomposition, several investigations have shown that bulk sediment $\delta^{13}C$ values are incorporated into coastal sedimentary archives in a manner allowing reliable identification of floral zones after more than 3000 years (Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004; Lamb *et al.*, 2007). These studies suggested that fractionation of bulk sediment $\delta^{13}C$ is most pronounced during the short period following deposition of dead plant material and that bulk sediment underwent little further change. In core EF10, consistency of $\delta^{13}C$ values between depths of 0.05 m and 2.80 m (14.8‰ ± 0.8; 1σ) suggests that no systematic, post-depositional shift can be discerned in bulk sediments with a floral origin dominated by C_4 plants, corresponding to approximately 1450 years (Figure 6).

At Leeds Point two parallel transects were established (Figures 1 and 2) to investigate intra site variability in measured sediment $\delta^{13}C$ values. Most previous studies used single transects and sought to describe variability among sites (Wilson *et al.*, 2005a, 2005b; Kemp *et al.*, 2010). Implicit in paleoenvironmental interpretations based upon single transects is an assumption that small-scale (within a floral zone at a single marsh) variability is not significant. On salt marshes, variability of this kind may occur due to spatial changes in allochthonous inputs (Gebrehiwet *et al.*, 2008) or differing decomposition in pockets of aerobic rather than anoxic sediment. Transects at Leeds Point showed a consistent pattern of measured $\delta^{13}C$ values (Figure 2b). Sediments from floral zones dominated by C_3 plants on transect A-A' had an average $\delta^{13}C$ value of -25.8‰ (-27.0‰ to -22.7‰) compared to -25.8‰ (-26.7‰ to -22.9‰) on transect B-B'. Samples from 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‰). Equivalent samples from transect B-B' had an average $\delta^{13}C$ value of -16.8‰ (-17.6‰ to -16.2‰). Similarity between bulk sediment $\delta^{13}C$ values along the two transects at Leeds Point suggests that small-scale spatial variability was not significant.

5.4 Reconstructing Holocene relative sea-level changes

Establishing the botanical origin of bulk organic coastal sediments offers a means to reconstruct sea level by estimating the elevation at which a sediment sample formed and was deposited (Tornqvist *et al.*, 2004; Tornqvist *et al.*, 2006; Johnson *et al.*, 2007). Whilst there is no direct correlation between elevation and measured $\delta^{13}C$ values (Kemp *et al.*, 2010) (Figure 5), recognition of floral zones in an appropriate stratigraphical context allows relative sea level to be reconstructed. To consider the use of bulk sediment $\delta^{13}C$ values as a sea-level indicator in southern New Jersey we estimated the indicative meaning of 91 samples from a core (EF10) at Leeds Point (Figures 1 and 5). These estimates and interpretations are reliant upon the underlying assumption that plant species have maintained their ecological preferences and physiography throughout the period under consideration, including the present.

We recognized four indicative meanings that could be assigned to samples in core EF 10 (Table 2).

1) δ^{13}C values less depleted than -18.9‰ formed between MTL and MHHW.

Measured δ^{13}C values in modern bulk sediment did not distinguish between low and high-marsh floral zones as both were dominated by C_4 plants (Figure 5). The range of measured δ^{13}C sediment values from these environments in New Jersey was -18.9‰ to -15.4‰. As such, we recognized a salt-marsh environment as having δ^{13}C values less depleted 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 (Table 2). Under current tidal conditions at Leeds Point, the range from MTL to MHHW is 0.59 m.

The sample at 1.8 m provides a unique example (in this core) of how δ^{13}C values can be applied in relative sea level reconstructions. No foraminifera were present in the sample, which was unusual given the nature of nearby samples; it had a δ^{13}C value of -15.2‰ (Figure 6). A bulk sediment δ^{13}C measurement less depleted than -18.9‰ allowed this sample to be classified as having a salt-marsh origin typical of modern sites in New Jersey in light of its stratigraphic context and organic-rich nature. This example demonstrates how δ^{13}C can be used to reconstruct relative sea level in some instances where foraminifera (or other sea-level indicators) are not preserved or cannot be used for other reasons.

2) $\delta^{13}C$ values more depleted 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 in New Jersey could not be separated using $\delta^{13}C$ values because both were dominated by C_3 plants (Figure 5). As such, core samples having $\delta^{13}C$ values associated with C_3 plants (more depleted than -22.0‰) could only be said to have formed at an elevation above MHHW. In studies seeking to reconstruct relative sea level, such samples should be restricted to establishing freshwater limiting points, which constrain only the upper altitude of former sea level (Shennan and Horton, 2002; Engelhart *et al.*, In Press). Foraminifera were absent in all samples below 3.95 m and in a sample at 1.80 m (Kemp et al.; Figure 6).

3) $\delta^{13}C$ values more depleted than -22.0‰ with presence of agglutinated foraminifera formed between MHHW and HAT.

In southern New Jersey, foraminifera are absent in modern freshwater upland sediments, whilst modern brackish sediments included agglutinated taxa such as *Jadammina macrescens* and *Haplophragmoides manilaensis* (Kemp et al. in review). Therefore samples with $\delta^{13}C$ values typical of C_3 plants and presence of foraminifera were associated with brackish conditions and given a PME of MHHW to HAT (Table 2).

Under current tidal conditions at Leeds Point the elevational range between MHHW and HAT is 0.51m.

4) Samples with intermediate $\delta^{13}C$ values (-22.0‰ to -18.9‰) and presence of agglutinated foraminifera formed between MTL and HAT

The floral origin of samples with intermediate $\delta^{13}C$ values is unclear, although presence of agglutinated foraminifera indicates an intertidal origin. Samples of this nature were given a PME of MTL to HAT to reflect this uncertainty, which corresponds to a 0.90 m range at Leeds Point today (Figure 6).

Samples from core EF10 at depths below 3.95 m had $\delta^{13}C$ values of -26.8‰ to -25.4‰ (Figure 6). Foraminifera were absent in all of these samples (Figure 6), therefore we assigned a PME of above MHHW. Between 3.95 m and 2.80 m, 29 samples had measured $\delta^{13}C$ values from -27.0‰ to -16.2‰. Agglutinated foraminifera were present in all of these samples. Of this group, 24 samples were more depleted than -22.0‰ and coupled with the presence of agglutinated foraminifera were considered to represent brackish conditions and assigned a PME of MHHW to HAT. Five samples had transitional $\delta^{13}C$ values (between the ranges of C_3 and C_4 plants) and were assigned a conservative PME 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 PME of MTL to MHHW (Figure 6).

Bulk sediment $\delta^{13}C$ values that are synonymous with a dominance of C_4 plants may be used to reconstruct relative sea level in instances where the sedimentary context of a sample and modern transects supports its interpretation of having a salt-marsh origin. Relative sea level is reconstructed by subtracting estimated PME from measured altitude (with respect to the same tidal datum) for each sample. 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 vegetated salt marshes (van de Plassche, 1991; Gehrels, 1994; Middleburg *et al.*, 1997). The absolute elevational range corresponding to MTL-MHHW varies among and within these regions due to differences in tidal range, making the potential precision of this approach geographically variable. The threshold used for distinguishing such samples would vary slightly depending on the modern data used, but was less than 2‰ among the modern sites we documented. Appropriate modern datasets describing the distribution of plants with respect to tidal datums and of sufficient scope to include salt marsh, brackish and upland floral zones are necessary to calibrate paleoenvironmental interpretations of $\delta^{13}C$ values.

Understanding changes in plant community and subsequently relative sea level using core 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 these samples be used as freshwater limiting points in instances where only $\delta^{13}C$ values are available for interpretation. However, presence of agglutinated foraminifera in such samples allows them to estimate PME, because their distribution is restricted to intertidal environments. Indeed, the combination of a C_3 $\delta^{13}C$ value and presence of agglutinated foraminifera in New Jersey (and similar regions) restricts estimated PME to the interval between MHHW and HAT, which is a more precise interpretation than is possible from C_4 $\delta^{13}C$ values either in isolation or with the presence of agglutinated foraminifera. One reason for investigating the use of stable carbon isotopes to reconstruct sea level was to provide an instrumental means to measure sea-level indicators rather than relying on time consuming and specialist counting of microfossils such as foraminifera. However, determining presence or absence of agglutinated foraminifera can be done quickly, cheaply and with minimal consideration of taxonomy.

In contrast to New Jersey and similar regions, 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 such as *Distichlis spicata* do exist as patches 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 relative sea-level reconstruction by (Kemp *et al.*, 2010). In such settings it is challenging to distinguish among fresh, brackish and high salt-marsh floral zones using $\delta^{13}C$ values. Therefore the indicative meanings of $\delta^{13}C$ values described from New Jersey are not applicable in regions with different salt marsh biomes or to buried sediments that formed in these circumstances. The modern geographic division between these salt-marsh ecological regions on the Atlantic coast of the USA is shown by marked 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 further north (Eleuterius, 1976).

5.5 Implications for understanding salt-marsh evolution

Core EF10 provides some insight into how salt marshes were established at Leeds point and the relative usefulness of stable carbon isotopes and foraminifera for establishing the floral and environmental origin of sediments beneath salt marshes. The lowermost section of core EF10 consists of sand and gravel that is likely a glacial outwash deposit (Figure 6). This unit is overlain by unstructured, organic-rich, sediment (up to 40.8% TOC) from 4.2 m to 3.2 m, with plant macrofossils above 4.16 m determined to be *Phragmites australis*. Agglutinated foraminifera were present above 3.95m (Figure 6). We recognize this unit as a brackish salt marsh to upland transition at depths above 3.95 m and assigned indicative meaning reflecting this interpretation. Understanding the most basal section is difficult because $\delta^{13}C$ values suggest a brackish or freshwater origin which cannot be distinguished in the absence of foraminifera. The presence of *Phragmites australis* plant macrofossils indicates a brackish origin, but could represent downward growth into freshwater sediment. A salt-marsh peat between 2.8 m and 0.7 m and was recognized by $\delta^{13}C$ values less depleted than -18.9‰ with agglutinated foraminifera and abundant plant macrofossils typical of modern New Jersey salt marshes. The uppermost 0.7 m of the core was composed of organic silt and likely reflects anthropogenic alteration of the salt marsh (ditching).

The interval between 3.2 m and 2.8 m in core EF10 spans the environmental change from a brackish transitional zone to salt-marsh floral community. Measured $\delta^{13}C$ values displayed clear variability (-24.5‰ to -16.4‰) and were frequently transitional between values associated with C_3 and C_4 floral zones (-22.0‰ to -18.9‰; Figure 6). We propose that this period of variability represents encroachment of the salt-marsh floral environment that persists until today on a brackish transitional zone. Radiocarbon dates show that this environmental change took approximately 350 years (1806 at 3.27 m to 1452 years BP at 2.82 m; Figure 6) to be manifest in measured $\delta^{13}C$ values, although uncertainty in measurement and calibration can accommodate a period of between 207 and 501 years. A study focused on evolution of salt marsh conditions in North Carolina concluded that it would take more than 200 years for bulk sediment to develop the characteristics of a *Spartina patens* high salt marsh along the border of a freshwater upland, even though the plant community is able to establish itself in three to five years (Craft *et al.*, 2002). However, the trajectories of such developments are likely to be non-linear and effected by other changes during that time such as climate variability (Craft *et al.*, 2002). Radiocarbon dates and $\delta^{13}C$ values from core EF10 suggest that bulk sediment may have taken 350 years to reflect a change in salt-marsh floral community, although 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.

6 Conclusions

We investigated the use of $\delta^{13}C$ values measured in bulk organic sediment to establish the botanical origin of samples from coastal sedimentary archives in New Jersey, USA as a means to reconstruct relative sea level. Modern transects established at 3 sites with a total of 61 samples showed that sediment derived from C_4 plants had $\delta^{13}C$ values from -18.9‰ to -15.8‰ and included both a low salt-marsh zone vegetated by *Spartina alterniflora* (tall form) and a high salt-marsh floral zone dominated by *Spartina patens* and *Spartina alterniflora* (short form). In contrast, bulk sediment associated with C_3 plants was characterized by $\delta^{13}C$ 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 the Leeds Point site demonstrated that there was no discernible intra-site variability between samples of the same floral origin. Comparison of sediment $\delta^{13}C$ values with examples of living plants from the study sites showed that *Spartina* spp. underwent diagentic change shortly after deposition (up to 6.5‰), but then likely remained unchanged for 1500 years. Changes to *Phragmites australis* were less than 2‰. We used 91 samples from a core collected at the Leeds Point salt marsh to investigate the use of $\delta^{13}C$ values for establishing the botanical origin of sediments. Four classifications of samples were proposed;

1) Those with $\delta^{13}C$ values less depleted than -18.9‰ were conservatively interpreted as having formed on a vegetated salt marsh between mean tide level (MTL) and highest astronomical tide (HAT). Such an interpretation remains valid in the absence of foraminifera as shown by one example in core EF10.

2) Sediment more depleted than -22.0‰ and containing agglutinated foraminifera formed in a brackish transitional zone between MHHW and HAT. This classification had the

greatest degree of vertical precision. Documenting presence or absence of agglutinated foraminifera can be achieved quickly and with minimal taxonomic training, making this combination a useful sea-level indicator.

3) Sediment more depleted than -22.0‰ and lacking foraminifera formed above MHHW and maybe unrelated to former sea level. It was therefore is restricted establishing limiting data. The inability of $\delta^{13}C$ values to distinguish brackish and freshwater-derived sediments is its primary limitation in New Jersey and similar regions.

4) Caution dictates that samples with intermediate $\delta^{13}C$ values (-22.0‰ to -18.9‰) be interpreted as having formed between MTL and HAT, reflecting uncertainty in determining floral origin.

Core EF10 records the change from a brackish transitional environment to a salt marsh that persists until the present. A 0.4 m thick section spans the change between these two environments and is typified by intermediate or transitional $\delta^{13}C$ values. Radiocarbon dating suggests that this change took place between 1807 and 1452 years before present. This period is broadly similar to empirical predictions of the time needed for bulk organic sediment to assume the characteristics of a new dominant vegetation, and specifically the change from a C_3 to C_4 dominated zone.

Acknowledgements

Funding for this study was provided by NICRR grant DE-FC02-06ER64298 and National Science Foundation award EAR-0951686. C.H. Vane publishes with permission of the Executive Director of British Geological Survey. We thank C. Kendrick and M. Leng for stable carbon isotope measurements (National Isotope Geosciences Laboratory, UK). Kemp thanks a graduate internship at the National Ocean Sciences Accelerator Mass Spectrometry laboratory (Woods Hole) and Mark Roberts for radiocarbon support. Engelhart was supported by the USDA Forest Service Global Change Research Program of the Northern Research Station. This research was supported by Earthwatch Institute Student Challenge Award Programs and we thank the students who participated so enthusiastically in fieldwork. The Edwin Forsythe National Wildlife Refuge (U.S. Fish and Wildlife Service) is acknowledged for their co-operation and for providing access to study sites. Jerry Mead (Academy of Natural Science, Philadelphia) kindly provided us with use of the RTK. This paper is a contribution to IGCP project 588 “Preparing for coastal change” and PALSEA.

Figure Captions

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 stable carbon isotopes, C:N and total organic carbon along transects at each sites. A core (EF10) was recovered from Leeds Point for analysis (A).

Figure 2: Stable carbon isotopes along two transects (A-A' and B-B') from Leeds Point. Left panels show results from transect A (A-A'); right panels show results from transect B (B-B'). (A, E) Elevation profiles of transects including zonation of vascular vegetation. (B, F) Measured $\delta^{13}C$ values from bulk surface sediment samples; (C, G) total organic carbon (TOC) and (D, H) C:N ratios measured in bulk surface sediment samples along the transects. Black and white 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 3: Stable carbon isotopes along a transect (C-C') at Bass River. (A) Elevation profile of the transect including zonation of vascular vegetation. (B) Measured $\delta^{13}C$ values from bulk surface sediment sample; (C) total organic carbon (TOC) and (D) C:N ratios measured in bulk surface sediment samples along the transects. Black and white 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: Stable carbon isotopes along a 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 measured in bulk surface sediment samples along the transects. Black and white 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 5: 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) to allow comparison among sites with different tidal ranges. Tidal datums are shown for reference. Symbols represent the floral environment from which samples were collected and symbol shading denotes site. Grey 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.

Figure 6: Measured values of $\delta^{13}C$, 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, C_4 and transitional values are limits established from the four modern transects. Filled circles show position of radiocarbon dates with mid-point ages. Downcore presence of agglutinated foraminifera typical of salt marshes (SMF) is shown by filled bars, while open bars show samples in which no

foraminifera were present (from Kemp et al., in review). Paleomarsh elevation (PME, right panel) was estimated for samples with $\delta^{13}C$ values typical of C_4 salt-marsh plants as mean tide level (MTL) to mean higher high water (MHHW). Samples with $\delta^{13}C$ values associated with C_3 plants and the presence of agglutinated foraminifera were assigned a PME from MHHW to highest astronomical tide (HAT). Samples with $\delta^{13}C$ values associated with C_3 plants and no salt-marsh foraminifera were assumed to have formed above MHHW (indicated by the arrow). MLW = mean low water.

Table 1: Radiocarbon ages

Depth (m)	^{14}C Age	$\delta^{13}C$	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 on from core EF10. Ages at 2.68 m and 2.45 m were derived from extended AMS 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). $\delta^{13}C$ 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 $\delta^{13}C$ fractionation by the reporting laboratory.

Table 2

Floral Zone	**Dominant Vegetation**	**Elevational Range**	δ^{13}**C** (‰)
Low salt marsh	*Spartina alterniflora (tall form)*	MSL 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^1 Above MHHW^2	<-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 (^{1}), or absence (^{2}), of agglutinated salt-marsh foraminifera that are not present in modern freshwater upland environments (above HAT).

References

Benner R, Fogel, ML, Sprague, EK. 1991. Diagenesis of belowground biomass of Spartina alterniflora in salt-marsh sediments. Limnology and Oceanography ***36****: 1358-1374.*

Benner R, Fogel, ML, Sprague, EK, Hodson, RE. 1987. Depletion of ^{13}C in lignin and its implications for stable isotope studies. Nature ***329****: 708-710.*

Buchan A, Newell, SY, Butler, M, Biers, EJ, Hollibaugh, JT, Moran, MA. 2003. Dynamics of bacterial and fungal communities on decaying salt marsh grass. Applied and Environmental Microbiology ***69****: 6676-6687.*

Byrne R, Ingram, BL, Starratt, S, Malamud-Roam, F, Collins, JN, Conrad, ME. 2001. Carbon-Isotope, Diatom, and Pollen Evidence for Late Holocene Salinity Change in a Brackish Marsh in the San Francisco Estuary. Quaternary Research ***55****: 66-76.*

Chapman VJ. 1960. Salt Marshes and Salt Deserts of the World. Interscience Publishers, New York.

Chmura GL, Aharon, P. 1995. Stable carbon isotope signatures of sedimentary carbon in coastal wetlands as indicators of salinity regime. Journal of Coastal Research ***11****: 124-135.*

Chmura GL, Aharon, P, Socki, RA, Abernethy, R. 1987. An inventory of ^{13}C abundances in coastal wetlands of Louisiana, USA: vegetation and sediments. Oecologia ***74****: 264-271.*

Choi Y, Wanng, Y, Hsieh, YP, Robinson, L. 2001. Vegetation succession and carbon sequestration in a coastal wetland in northwest Florida: evidence from carbon isotopes. Global Biogeochemical Cycles ***15****: 311-319.*

Cloern JE, Canuel, EA, Harris, D. 2002. Stable Carbon and Nitrogen Isotope Composition of Aquatic and Terrestrial Plants of the San Francisco Bay Estuarine System. Limnology and Oceanography ***47****: 713.*

Craft C, Broome, S, Campbell, C. 2002. Fifteen years of vegetation and soil development after brackish-water marsh creation. Restoration Ecology ***10****: 248-258.*

Craft CB, Broome, SW, Seneca, ED, Showers, WJ. 1988. Estimating sources of soil organic matter in natural and transplanted estuarine marshes using stable isotopes of carbon and nitrogen. Estuarine Coastal and Shelf Science ***26****: 633-641.*

Currin CA, Newell, SY, Paerl, HW. 1995. The role of standing dead Spartina alterniflora and benthic microalgae in salt marsh food webs: considerations based on multiple stable isotope analysis. Marine Ecology Progress Series ***121****: 99-116.*

Daddario JJ. 1961. A lagoon deposit profile near Atlantic City, New Jersey. Bulletin of the New Jersey Academy of Science **6**: *7-14.*

DeLaune RD. 1986. The use of δ^{13}*C signature of C-3 and C-4 plants in determining past depositional environments in rapidly accreting marshes of the Mississippi River deltaic plain, Louisiana, U.S.A. Chemical Geology: Isotope Geoscience section* **59**: *315-320.*

Dolan R, Hayden, B, Rea, C, Heywood, J. 1979. Shoreline erosion rates along the middle Atlantic coast of the United States. Geology **7**: *602-606.*

Edwards RJ. 2007. Sea Level Studies: Low energy coasts sedimentary indicators, In Encyclopedia of Quaternary Science, Elias SA editor. Elsevier; Amsterdam; 2994-3005.

Edwards RJ, Wright, AJ, van de Plassche, O. 2004. Surface distributions of salt-marsh foraminifera from Connecticut, USA: modern analogues for high-resolution sea level studies. Marine Micropaleontology **51**: *1-21.*

Eleuterius L. 1976. The distribution of Juncus roemerianus in the salt marshes of North America. Chesapeake Science **17**: *289.*

Ember LM, Williams, DF, Morris, JT. 1987. Processes that influence carbon isotope variations in salt marsh sediments. Marine Ecology Progress Series **36**: *33-42.*

Emery KO, Wigley, RL, Bartlett, AS, Rubin, M, Barghoorn, ES. 1967. Freshwater peat on the continental shelf. Science **158**: *1301-1307.*

Engelhart SE, Peltier, WR, Horton, BP. In Press. Holocene relative sea-level changes and glacial isostatic adjustment of the U.S. Atlantic coast. Geology

Ferland MA. 1990. Holocene depositional history of the southern New Jersey barrier and back barrier regions. US Army Corps of Engineers, p. 75.

Fitzgerald DM, Fenster, MS, Argow, BA, Buynevich, IV. 2008. Coastal Impacts Due to Sea-Level Rise. Annual Review of Earth and Planetary Sciences **36**: *601-647.*

Fogel ML, Kent Sprague, E, Gize, AP, Frey, RW. 1989. Diagenesis of organic matter in Georgia salt marshes. Estuarine, Coastal and Shelf Science **28**: *211-230.*

Fry B. 2006. Stable Isotope Ecology. Springer, New York.

Gebrehiwet T, Koretsky, CM, Krishnamurthy, RV. 2008. Influence of Spartina and Juncus on saltmarsh sediments III; organic geochemistry. Chemical Geology **255**: *114-119.*

Gehrels WR. 1994. Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, U.S.A. Journal of Coastal Research **10**: *990-1009.*

Goñi M, Thomas, K. 2000. Sources and transformations of organic matter in surface soils and sediments from a tidal estuary (North Inlet, South Carolina, USA). Estuaries and Coasts ***23****: 548-564.*

González JL, Törnqvist, TE. 2009. A new Late Holocene sea-level record from the Mississippi Delta: evidence for a climate/sea level connection? Quaternary Science Reviews ***28****: 1737-1749.*

Haddad RI, Newell, SY, Martens, CS, Fallon, RD. 1992. Early diagenesis of lignin-associated phenolics in the salt marsh grass Spartina alterniflora. Geochimica et Cosmochimica Acta ***56****: 3751-3764.*

Haines EB. 1976. Stable carbon isotope ratios in the biota, soils and tidal water of a Georgia salt marsh. Estuarine Coastal Marine Science ***4****: 609-616.*

Johnson BJ, Moore, KA, Lehmann, C, Bohlen, C, Brown, TA. 2007. Middle to late Holocene fluctuations of C_3 and C_4 vegetation in a Northern New England Salt Marsh, Sprague Marsh, Phippsburg Maine. Organic Geochemistry ***38****: 394-403.*

Katalin VB, Mátyás, P, Lajos, V, Noémi, T. 2006. A study of the decomposition of reed (Phragmites australis) as a possible source of aquatichumic substances by measuring the natural abundance of stable carbon isotopes. International Review of Hydrobiology ***91****: 15-28.*

Kemp AC, Vane, CH, Horton, BP, Culver, SJ. 2010. Stable carbon isotopes as potential sea-level indicators in salt marshes, North Carolina, USA. The Holocene ***20****: 623-636.*

Lamb AL, Vane, CH, Wilson, GP, Rees, JG, Moss-Hayes, VL. 2007. Assessing $\delta^{13}C$ and C/N ratios from organic material in archived cores as Holocene sea level and palaeoenvironmental indicators in the Humber Estuary, UK. Marine Geology ***244****: 109-128.*

Lamb AL, Wilson, GP, Leng, MJ. 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth-Science Reviews ***75****: 29-57.*

Malamud-Roam F, Ingram, BL. 2001. Carbon Isotopic Compositions of Plants and Sediments of Tide Marshes in the San Francisco Estuary. Journal of Coastal Research ***17****: 17-29.*

Malamud-Roam F, Ingram, BL. 2004. Late Holocene $\delta^{13}C$ and pollen records of paleosalinity from tidal marshes in the San Francisco Bay estuary, California. Quaternary Research ***62****: 134-145.*

Matson EA, Brinson, MM. 1990. Stable carbon isotopes and the C:N ratio in the estuaries of the Pamlico and Neuse Rivers, North Carolina. Limnology and Oceanography ***35****: 1290-1300.*

Meyerson AL. 1972. Pollen and paleosalinity analyses from a Holocene tidal marsh sequence, Cape May County, New Jersey. Marine Geology ***12****: 335-357.*

Middleburg JJ, Nieuwenhuize, J, Lubberts, RK, van de Plassche, O. 1997. Organic carbon isotope systematics of coastal marshes. Estuarine Coastal and Shelf Science ***45****: 681-687.*

Niering WA, Warren, RS. 1980. Vegetation Patterns and Processes in New England Salt Marshes. BioScience ***30****: 301-307.*

Opsahl S, Benner, R. 1995. Early diagenesis of vascular plant tissues: Lignin and cutin decomposition and biogeochemical implications. Geochimica et Cosmochimica Acta ***59****: 4889-4904.*

Psuty NP. 1986. Holocene sea level in New Jersey. Physical Geography ***7****: 156-167.*

Redfield AC. 1972. Development of a New England salt marsh. Ecological Monographs ***42****: 201-237.*

Schlesinger WH. 1997. Global Biogeochemistry: An Analysis of Global Change. Academic Press.

Scott DB, Medioli, FS. 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea levels. Nature ***272****: 528-531.*

Shennan I. 1986. Flandrian sea-level changes in the Fenland. II: Tendencies of sea-level movement, altitudinal changes, and local and regional factors. Journal of Quaternary Science ***1****: 155-179.*

Shennan I, Horton, B. 2002. Holocene land-and sea-level changes in Great Britain. Journal of Quaternary Science ***17****: 511-526.*

Stuckey IH, Gould, LL. 2000. Coastal plants from Cape Cod to Cape Canaveral. University of North Carolina Press, Chapel Hill.

Stuiver M, Polach, HA. 1977. Reporting of ^{14}*C data. Radiocarbon* ***19****: 355-363.*

Stuiver M, Reimer, PJ. 1993. Extended ^{14}*C database and revised Calib 3.0* ^{14}*C age calibration program. Radiocarbon* ***35****: 215-230.*

Tanner BR, Uhle, ME, Kelley, JT, Mora, CI. 2007. C_3/C_4 variations in salt-marsh sediments: An application of compound specific isotopic analysis of lipid biomarkers to late Holocene paleoenvironmental research. Organic Geochemistry ***38****: 474-484.*

Thorbjarnarson KW, Nittrouer, CA, DeMaster, DJ, McKinney, RB. 1985. Sediment accumulation in a back-barrier lagoon, Great Sound, New Jersey. Journal of Sedimentary Research ***55****: 856-863.*

Tornqvist TE, Bick, SJ, van der Borg, K, de Jong, AFM. 2006. How stable is the Mississippi Delta? Geology ***34****: 697-700.*

Tornqvist TE, Gonzalez, JL, Newsom, LA, van der Borg, K, de Jong, AFM, Kurnik, CW. 2004. Deciphering Holocene sea-level history on the US Gulf Coast: a high-resolution record from the Mississippi Delta. Geological Society of America Bulletin ***116****: 1026-1039.*

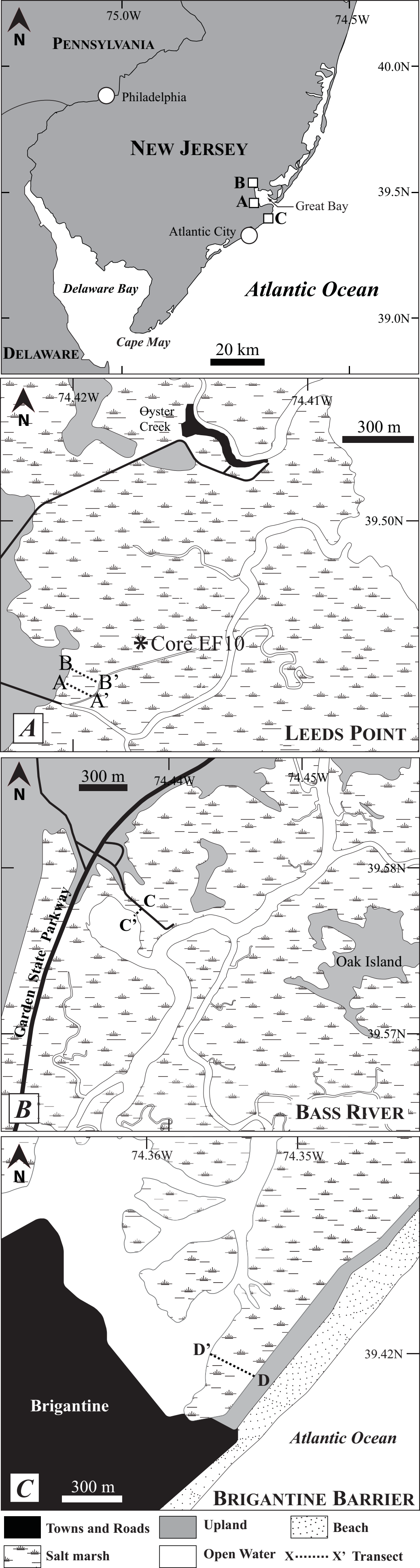
van de Plassche O. 1986. Sea-level research: a manual for the collection and evaluation of data, In: van de Plassche O (Ed.). Geobooks, Norwich, p. 618.

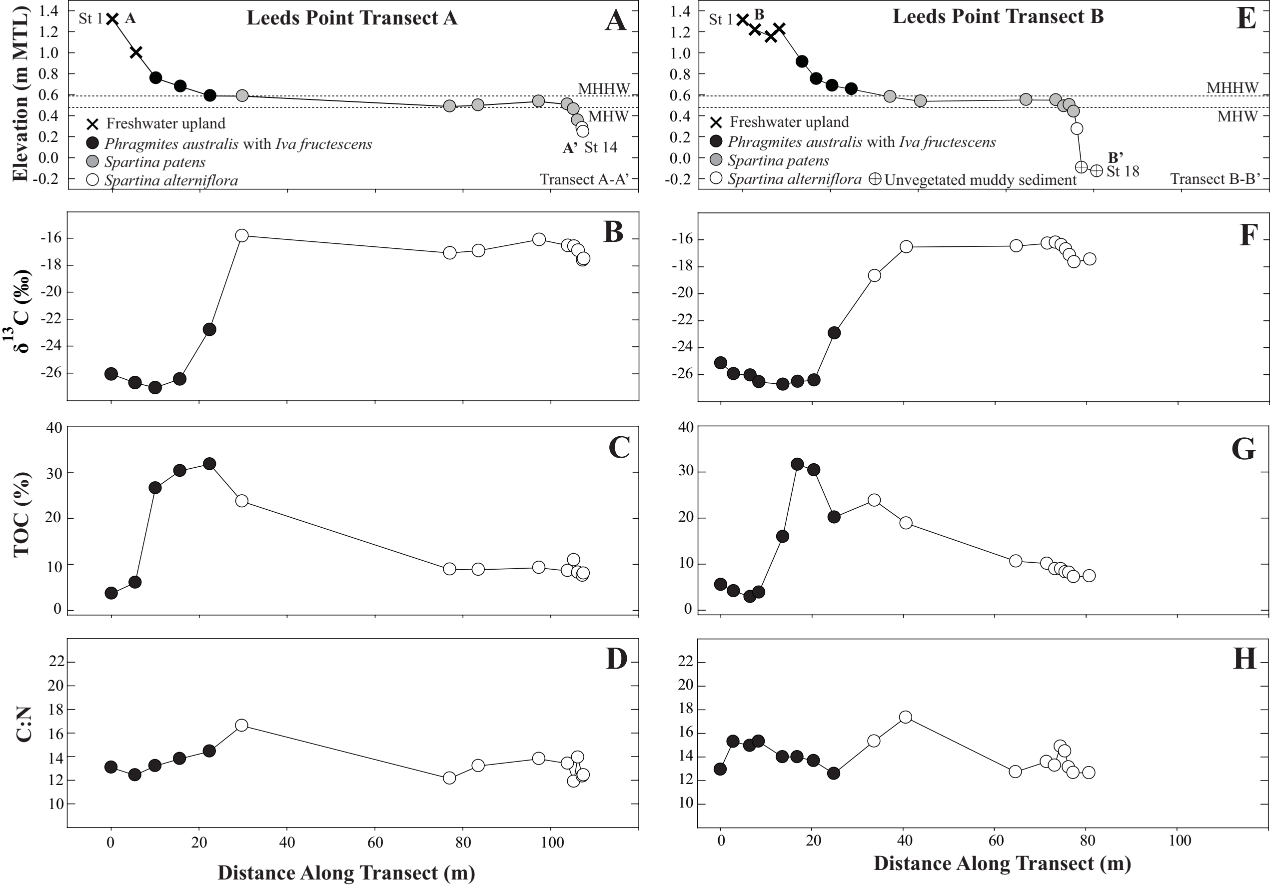
van de Plassche O. 1991. Late Holocene sea-level fluctuations on the shore of Connecticut inferred from transgressive and regressive overlap boundaries in salt-marsh deposits. Journal of Coastal Research ***11****: 159-179.*

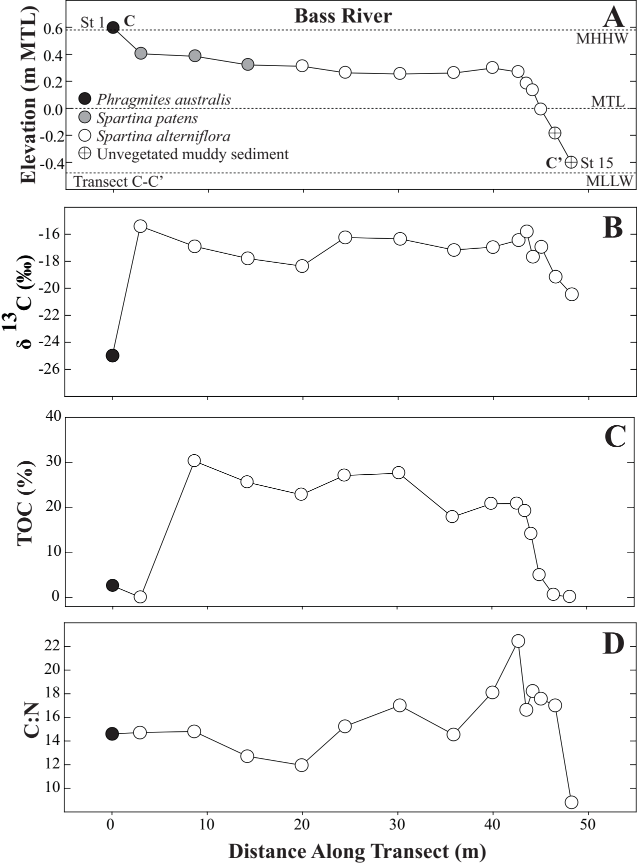
Wilson GP, Lamb, AL, Leng, MJ, Gonzalez, S, Huddart, D. 2005a. $\delta^{13}C$ and C/N as potential coastal palaeoenvironmental indicators in the Mersey Estuary, UK. Quaternary Science Reviews ***24****: 2015-2029.*

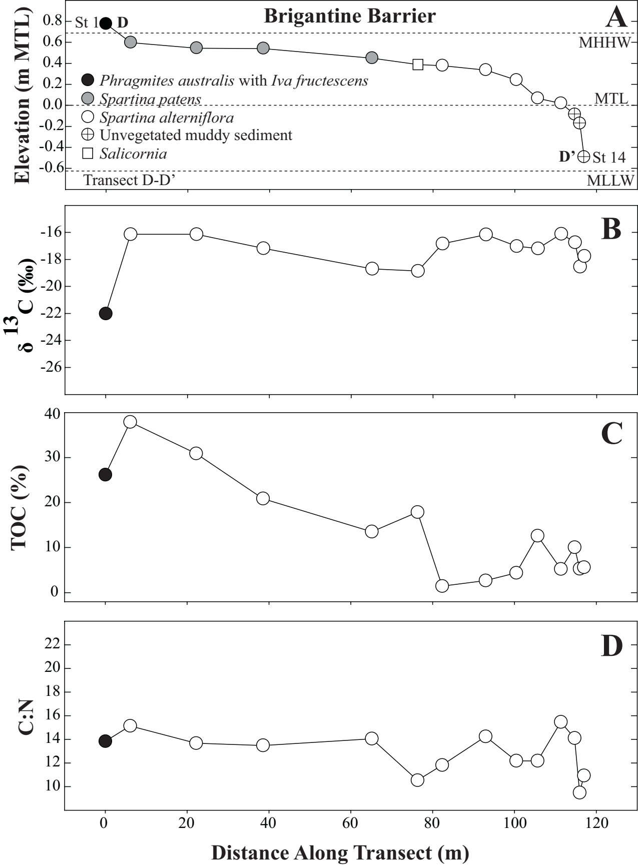
Wilson GP, Lamb, AL, Leng, MJ, Gonzalez, S, Huddart, D. 2005b. Variability of organic $\delta^{13}C$ and C/N in the Mersey Estuary, U.K. and its implications for sea-level reconstruction studies. Estuarine, Coastal and Shelf Science ***64****: 685-698.*

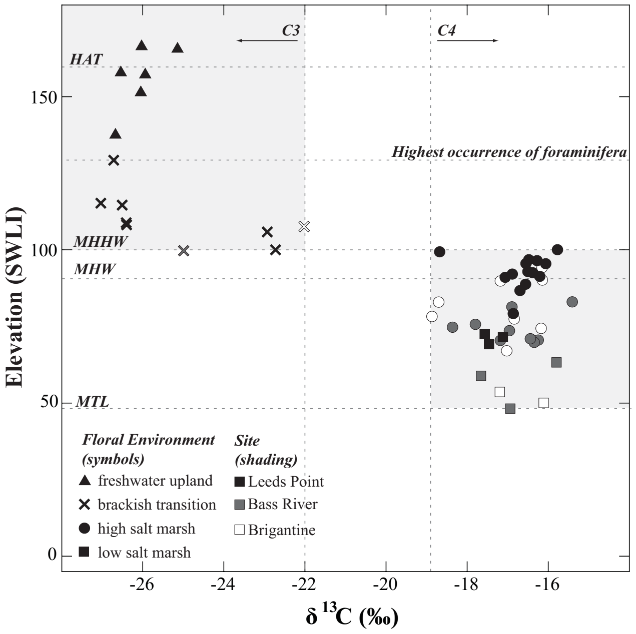
Yang Z, Myers, EP, Wong, A, White, S. 2008. Vdatum for Chesapeake Bay, Delaware Bay, and Adjacent Coastal Water Areas: Tidal Datums and Sea surface Topography, NOAA Technical Memorandum NOS CS 15. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, p. 110.

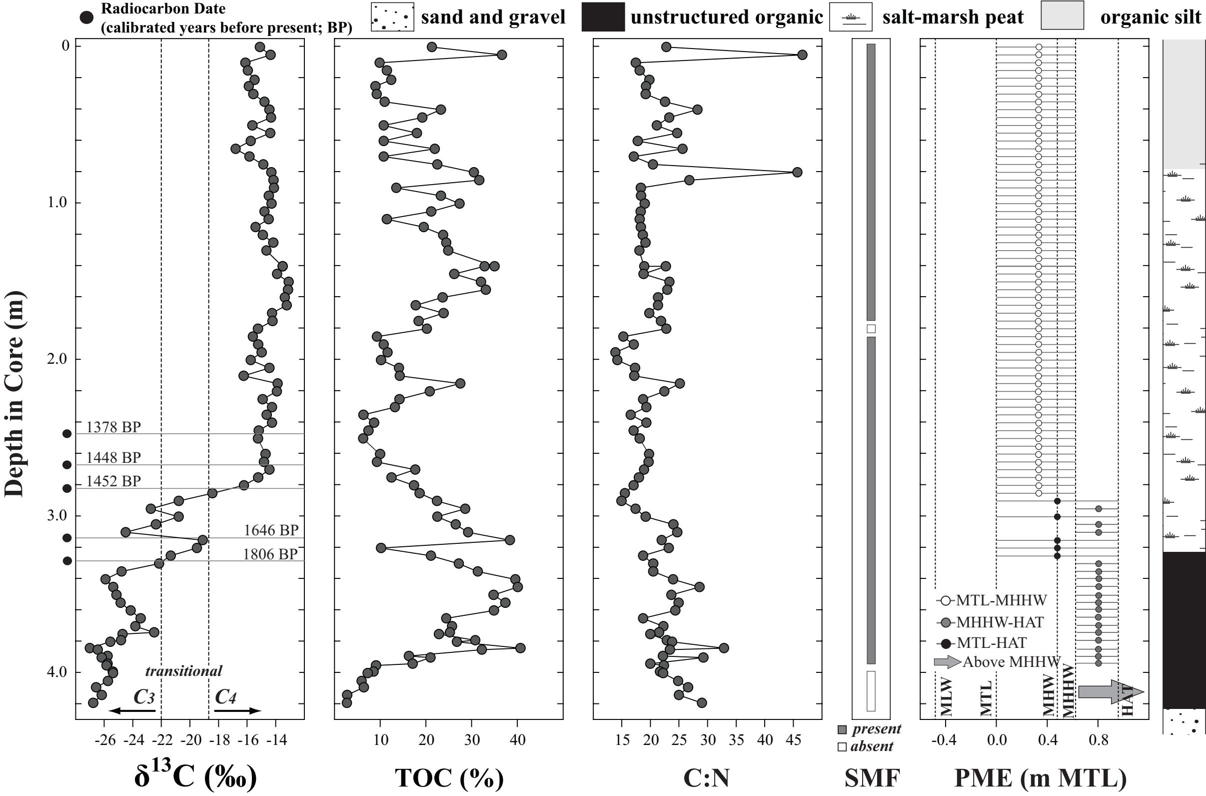

N
75.0W
74.5W
PENNSYLVANIA
40.0N
Philadelphia
NEW JERSEY
B
A
Great Bay
39.5N
C
Atlantic City
Delaware Bay
Atlantic Ocean
39.0N
Cape May
DELAWARE
20 km
N
74.42W
Oyster Creek
74.41W
300 m
39.50N
Core EF10
B
B'
A
A'
A
LEEDS POINT
N
300 m
74.44W
74.45W
39.58N
Garden State Parkway
C
C'
Oak Island
39.57N
B
BASS RIVER
N
74.36W
74.35W
D'
39.42N
D
Brigantine
Atlantic Ocean
C
300 m
BRIGANTINE BARRIER
Towns and Roads
Upland
Beach
Salt marsh
Open Water
X....... X' Transect


Leeds Point Transect A
Leeds Point Transect B
A
B
C
D
E
F
G
H
St 1
A
A' St 14
St 1
B
B'
St 18
MHHW
MHW
Transect A-A'
Transect B-B'
× Freshwater upland
● *Phragmites australis* with *Iva fructescens*
● *Spartina patens*
○ *Spartina alterniflora*
⊕ Unvegetated muddy sediment
Elevation (m MTL)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
δ13C (‰)
-16
-18
-20
-22
-24
-26
TOC (%)
40
30
20
10
0
C:N
22
20
18
16
14
12
10
0
20
40
60
80
100
Distance Along Transect (m)


Bass River
A
St 1
C
MHHW
MTL
MLLW
C'
St 15
Transect C-C'
● Phragmites australis
● Spartina patens
○ Spartina alterniflora
⊕ Unvegetated muddy sediment
Elevation (m MTL)
0.6
0.4
0.2
0.0
-0.2
-0.4
B
δ13C (‰)
-16
-18
-20
-22
-24
-26
C
TOC (%)
40
30
20
10
0
D
C:N
22
20
18
16
14
12
10
0
10
20
30
40
50
Distance Along Transect (m)


Brigantine Barrier
A
St 1
D
MHHW
MTL
MLLW
D'
St 14
Transect D-D'
● *Phragmites australis* with *Iva fructescens*
● *Spartina patens*
○ *Spartina alterniflora*
⊕ Unvegetated muddy sediment
□ *Salicornia*
Elevation (m MTL)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
B
δ 13C (‰)
-16
-18
-20
-22
-24
-26
C
TOC (%)
40
30
20
10
0
D
C:N
22
20
18
16
14
12
10
0
20
40
60
80
100
120
Distance Along Transect (m)


C3
C4
HAT
Highest occurrence of foraminifera
MHHW
MHW
MTL
Elevation (SWLI)
150
100
50
0
-26
-24
-22
-20
-18
-16
δ 13C (‰)
Floral Environment (symbols)
▲ freshwater upland
✕ brackish transition
● high salt marsh
■ low salt marsh
Site (shading)
■ Leeds Point
■ Bass River
□ Brigantine


Radiocarbon Date
(calibrated years before present; BP)
sand and gravel
unstructured organic
salt-marsh peat
organic silt
Depth in Core (m)
0
1.0
2.0
3.0
4.0
1378 BP
1448 BP
1452 BP
1646 BP
1806 BP
transitional
C3
C4
-26
-24
-22
-20
-18
-16
-14
δ13C (‰)
10
20
30
40
TOC (%)
15
20
25
30
35
40
45
C:N
present
absent
SMF
MTL-MHHW
MHHW-HAT
MTL-HAT
Above MHHW
MLW
MTL
MHW
MHHW
HAT
-0.4
0.0
0.4
0.8
PME (m MTL)