

Field experiments on bioturbation in salt marshes (Bombay Hook National Wildlife Refuge, Smyrna, DE, USA): implications for sea-level studies

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Leorri, E., Martin, R. E. and Horton, B. P. 2009. Field experiments on bioturbation in salt marshes (Bombay Hook National Wildlife Refuge, Smyrna, DE, USA): implications for sea-level studies. *J. Quaternary Sci.*, Vol. 24 pp. 139–149. ISSN 0267-8179.

Received 25 June 2007; Revised 4 February 2008; Accepted 4 February 2008

ABSTRACT: The suitability of marsh sites for sea-level studies was examined based on field experiments along a transect from low to high marsh. Bead distributions were determined both seasonally and after 7 years. Seasonal sediment mixing was greatest in the low marsh and in the late spring and early summer, when biological activity is greatest. However, after an initial interval of relatively intense reworking, the bead concentrations reached an approximate equilibrium profile characteristic of each marsh environment as reflected by the profiles obtained after 7 years. Mixed-layer thickness is greatest (>10 cm) in the intermediate and low marsh, and burial rates are rapid (3.7–11.1 mm yr⁻¹). Moreover, burial rates are comparable to or even surpass longer-term (30 to >150 yr) radiotracer-derived sediment accumulation rates and rates of local and regional sea-level rise (~4 mm yr⁻¹). Therefore, sediment accumulation rates appear to reflect primarily sediment resuspension/redeposition within the system due to bioturbation. Thus, bioturbation may be critical to the ability of marshes to keep pace with sea level, while seemingly precluding the use of low marsh for high-resolution sea-level studies. Copyright © 2008 John Wiley & Sons, Ltd.



KEYWORDS: bioturbation; burial rates; temporal resolution; salt marsh; sea level.

Introduction

Global sea-level-rise (GSLR) is affecting coastal geomorphology, erosion and wetland loss (Gornitz, 1995; Leatherman, 2001; Nicholls, 2004). The GSLR rate for the last century has been estimated as ~1.8 mm yr⁻¹ (range 1.7–2 mm yr⁻¹) based on a number of high-quality tide gauge records (Douglas, 1995, 1997, 2001; Peltier and Jiang, 1997; Church *et al.*, 2004; Church and White, 2006; Bindoff *et al.*, 2007). More recent estimates of GSLR of ~3 mm yr⁻¹ became available based on satellite altimetry data beginning in 1993 (Cabanes *et al.*, 2001; Cazenave and Nerem, 2004; Leuliette *et al.*, 2004). The differences among GSLR estimates may be related to the acceleration of sea-level rise (0.013 ± 0.6 mm yr⁻²) found by Church and White (2006) for the period 1870–2000. However, these records are perhaps too short to infer pre-anthropogenic

(prior to AD 1850) sea-level changes (i.e., they span intervals of decades to approximately one century).

Estimating sea-level rise from sedimentary sequences of salt marsh peat has therefore received increasing attention. Salt marsh sediments are especially interesting because long-term accretion rates (>50 yr) approximate relative sea-level rise (Orson *et al.*, 1998; Reed, 2002). However, it is important to understand the sensitivity of marshes to both long- and short-term sea-level variations when attempting to utilise these systems in reconstructing historic sea-level changes (Orson *et al.*, 1998, and references therein). Recently, salt marsh studies have concentrated on quantifying the vertical relationships between biological proxies and tide level (Allen, 2003). These relationships are then employed to reconstruct past tide levels from core assemblages contained within sedimentary sequences (Gehrels, 2000; Horton and Edwards, 2006). Various researchers have suggested that assemblages of salt marsh foraminifera are the most accurate sea-level indicators of temperate coastlines, and exhibit a strong correlation with elevation above mean tidal level (MTL) (e.g. Scott and Medioli, 1978, 1986; Shennan *et al.*, 1996; Gehrels, 2000; Boski *et al.*, 2002; Gehrels *et al.*, 2001, 2005; Hayward *et al.*, 2004; Woodroffe *et al.*, 2005; Horton and Edwards, 2006; Southall *et al.*, 2006).

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Although foraminiferal assemblage diversity and abundance are influenced by many factors, studies from North America (Patterson *et al.*, 2004; Gehrels *et al.*, 2005), South America (Jennings *et al.*, 1995), Europe (Gehrels and Newman, 2004; Leorri *et al.*, 2008) and New Zealand (Southall *et al.*, 2006) indicate that the correlation between foraminiferal assemblage zone distribution and marsh elevation is recognisable worldwide. Considerable advances in sea-level reconstruction have been made in the last few years. These have centred on the development of microfossil transfer functions that quantify the vertical relationships between indicator species and tide level (e.g. Horton and Edwards, 2006). This type of approach is producing a new generation of high-resolution sea-level reconstructions (cm to m scale vertical resolution and annual to centennial scale age resolution) that is bridging the gap between short-term instrumental records and long-term, traditional geological reconstructions or geophysical predictions to investigate the relationship between climate and sea level at multi-decadal to centennial scales (e.g. Gehrels *et al.*, 2005). However, caution should be exercised when using transfer functions or other palaeoenvironmental reconstruction techniques because of post-depositional changes due to differential transport and preservation (taphonomy; Martin *et al.*, 2003).

One taphonomic aspect of the formation of marsh foraminiferal assemblages that has received less attention is that of sediment mixing, which results from a combination of both physical (e.g. tidal flushing) and biological processes (bioturbation) (Smoak and Patchineelam, 1999). Sediment mixing results in a reduction of temporal acuity, potentially affecting the resolution of the rates and magnitudes of sea-level change recorded in the sedimentary sequences. The reduction of temporal resolution appears to be most important in the low marsh (Hippensteel, 2005). Experimental studies indicate that considerable reworking and transport of the sediment must occur before its final burial in the marsh. This conclusion is based on the fact that the quantity of sediment deposited during two consecutive tides can often introduce several times the amount of sediment corresponding to the annual accretion rate (Boorman *et al.*, 2002).

Among the sediment-mixing processes, bioturbation is considered especially important in salt marshes. Here, fiddler crabs (*Uca* spp.) are one of the most numerous and conspicuous of burrowing intertidal macrofauna. Fiddler crabs rework the salt marsh surface between successive high tides; this is especially evident in areas of dense crab populations (Teal, 1962). These burrowing and reworking activities have a seasonal pattern, being particularly intense during the spring and summer when invertebrate activity and reproduction is greatest (Crane, 1943; Mouton and Felder, 1995). Fiddler crabs are abundant in salt marshes, salt flats and mangrove swamps along tropical, neotropical and temperate coastlines (Mouton and Felder, 1995; Koretsky *et al.*, 2005), including the mid-Atlantic coast of North America (Teal, 1958; Crane, 1975; Daiber, 1982). Other common burrowing organisms in salt marshes are snails (*Melampus bidentatus*), amphipods (*Orchestia grillus*), mussels (*Geukensia demissa*), shrimp (*Palaemonetes* spp.) and blue crabs (*Callinectes sapidus*) (Department of Natural Resources and Environmental Control and Delaware National Estuarine Research Reserve, 1999). Burrow distribution is heterogeneous both temporally and spatially. This heterogeneity is strongly affected by the presence of macrophyte roots (Teal, 1962; Michaud *et al.*, 2005). The roots of *Spartina alterniflora* Loise (which dominates intertidal salt marshes of the Atlantic coast of the USA; Mendelssohn and Morris, 2000) may extend to >55 cm below the surface (Gallagher and Plumley, 1979; Goldstein *et al.*, 1995),

inhibiting bioturbation. Since root densities are greatest in the high marsh, bioturbation is expected to be minimal in this subenvironment (Hippensteel *et al.*, 2000). However, plant densities decrease in the low marsh and burrow depths may increase to 30 cm or more (Sharma *et al.*, 1987; Goldstein *et al.*, 1995; Koretsky *et al.*, 2005).

Sediment-mixing intensity and accumulation rates vary with marsh elevation. Thus, salt marsh sites' suitability for high-resolution sea-level studies should also vary with elevation, but this has not been examined systematically with regard to these sedimentary processes. The present study therefore evaluates short-term (seasonal) and 7-yr (7-yr profiles) sediment mixing due to physical and biological processes, and its relation to sediment accumulation rates along an elevation gradient defined by high, mid and low marsh environments. Previous studies determined that bioturbation and mixed-layer thickness were greater in the low marsh than in the high marsh (Hippensteel *et al.*, 2002). Consequently, we hypothesise that sedimentary layers would remain relatively intact in the high marsh but would be mixed in the low marsh, thereby affecting the vertical and temporal component of sea-level reconstructions.

Study area

Bombay Hook National Wildlife Refuge (BHNWR) was selected as the study area because it is relatively pristine and has not been subject to widespread anthropogenic activities such as 'ditching' for mosquito control. It is located along the western shore of Delaware Bay near Smyrna, Delaware (Fig. 1). In Bombay Hook, marshes extend from the mouth (at the Delaware Bay) to the western extent of the refuge, and modern environments vary from freshwater tidal wetlands (to the west) to salt marsh environments to the east. Unlike other marshes with macrotidal ranges and distinct macrofloral zonations, the marshes along the Delaware River are characterised by a microtidal range (~1.5 m range) and the zonation of marsh macrophytes is therefore less distinct (see Fig. 1 for plant distribution in sampling area).

Bombay Hook salt marsh sediments consist of peat, mud and muddy-peat. Below the salt marsh sediment is a pre-transgressive lithofacies which has been described as fluvial or fluvial-tidal in origin (Nikitina *et al.*, 2000). The salt marsh lithosome thickness is between 1 and 1.5 m throughout much of Bombay Hook and has been the dominant environment during the last 1000 yr, as inferred from radiocarbon ages of basal peat samples (Nikitina *et al.*, 2000). In the northern Delaware marshes (including Bombay Hook) sedimentation rates average ~4 mm yr⁻¹ for the last 100 yr (Leorri *et al.*, 2006), which are similar to the observations of sea-level rise rates that range between 3 and 4 mm yr⁻¹ for the period 1900–2000 (data from the Permanent Service for Mean Sea Level).

Materials and methods

Within the salt marsh area we selected three plots, each measuring 1 m × 1 m, representing low, intermediate and high marsh plots (Hippensteel *et al.*, 2000). The plots were selected along a 21 m transect based on elevation, aerial exposure, plant distribution, and micropalaeontological analysis (see Hippensteel *et al.*, 2000) (Fig. 1). Elevations were measured with a

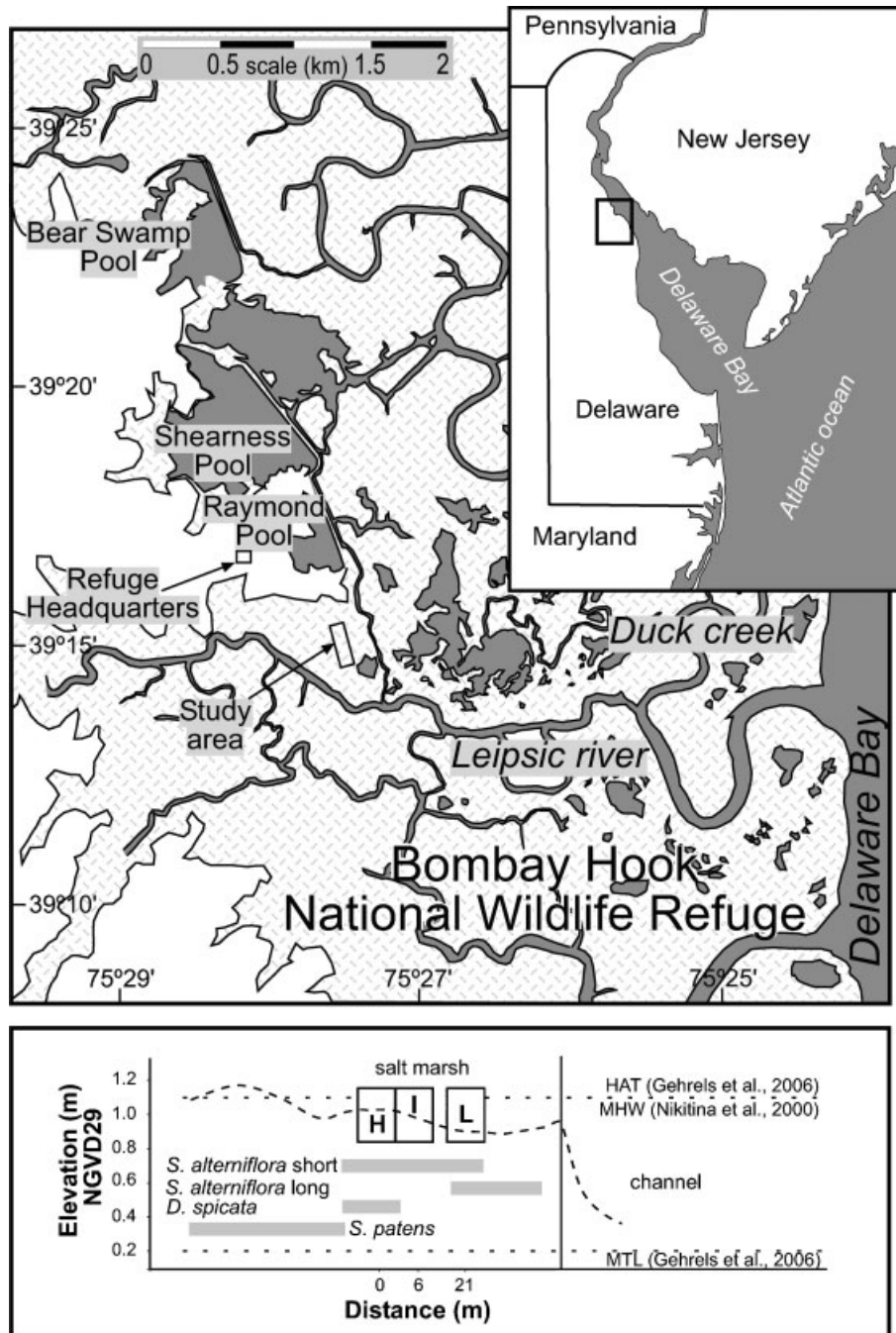


Figure 1 Location of Bombay Hook National Wildlife Refuge along Delaware Bay (USA). Lower box: dashed line represents marsh elevation relative to NGVD29 (m). Grey rectangles indicate plant distribution. Tidal references are indicated. HAT, highest astronomical tide; MTL, mean tidal level; MHW, mean high water. Sampling areas are indicated. H: high marsh plot; I: intermediate marsh plot; L: low marsh plot

Total Station and were corrected to National Geodetic Vertical Datum 1929 (NGVD 29). The high, intermediate and low marsh plots were found at 1.01, 0.98 and 0.90 m, respectively. Plant distribution is dominated by *S. alterniflora* short form, together with *Distichlis* in the high marsh plot and *S. alterniflora* long form in the low marsh plot. The higher high marsh (indicated by the presence of *Spartina patens* and bounded by the *Phragmites* and *Spartina cynosuroides* zone) is minimally impacted by sediment mixing, whereas lower elevations are highly impacted by sediment mixing (Hippensteel *et al.*, 2002). Therefore, these areas were excluded from the study.

We used chemically inert glass beads of two uniform sizes to determine sediment mixing rates: 'large' (180–250 μm) and 'small' (<105 μm ; JB Import & Export LLC, Franklin, NJ, USA). These two sizes were used in order to control possible

size-selective feeding, which is widespread among invertebrates. The beads were colour-coded by season to monitor rates of mixing: the red beads were spread in November 1997, yellow in July 1998 and green in September 1998. The beads were thoroughly mixed and spread as uniformly as possible over each plot with a hand-held grass seed spreader; the bead layer was then gently pressed into the sediment–water interface (SWI) with a large piece of plywood so as to minimise bead loss from tidal flooding.

We sampled each plot in February, June, July and September 1998 for red and yellow bead profiles, and April 2005 for all profiles. During sampling, each plot was subdivided into 5 cm \times 5 cm squares by aligning measuring tapes perpendicular to one another along the sides of each plot. The x–y coordinates of each of three squares within each plot were then selected

using a random number table. Grid numbers were chosen so that a newly sampled grid was never within ~30 cm of a previously sampled grid, and previously sampled grids were never resampled, so as to minimise possible contamination or anthropogenic mixing. For each pair of coordinates, we recovered a ~10 cm core by excavating a small block of sediment; 0–10 cm includes the zone of most intense plant root growth and geochemical alteration of sediment. During the April 2005 sampling period, we used a Russian peat corer to obtain 50 cm long cores. Compaction of the sediment during sampling was negligible. Because of the spatiotemporal variability of marshes (e.g. Buzas, 1968, 1970; Horton and Murray, 2007), two replicates were recovered from each plot. The work within the plots was always conducted from wooden planks so as not to disturb the marsh surface.

Upon return to the laboratory, we cut away the sides of the 10 cm sediment blocks and 50 cm cores to minimise artificial downcore smearing of beads during excavation, which would smear the tracer profile and thus overestimate mixing (Berg *et al.*, 2001). The sediment blocks were then sampled to the bottom by taking subsamples of 5 cm³ volume every 1 cm, whereas core samples were 10 cm³ volume. Subsamples were gently washed over stacked sieves ranging from 0.062–2.00 mm to remove plant macro-debris and fine sediment. Large and small beads were concentrated on 0.125 mm and 0.062 mm sieves, respectively. The beads collected on each sieve were washed separately into beakers, the contents swirled to concentrate beads in the bottom centre of the beaker and water was decanted with a pipette. The beads were then washed onto a gridded micropalaeontological counting tray and counted under a binocular microscope. Fifteen samples containing different numbers of beads were counted four times to determine the counting error as a function of sample size. For small beads, subsampling error was further estimated by counting two replicates from ten samples.

Bead counts were used to infer bioturbation rates. However, we emphasise that it is not the concentrations that are most important but the bead profiles (i.e., downcore patterns). Traditional bioturbation models describe mixing as a random diffusion process with a one-dimensional model incorporating all activities into a single parameter (Timmerman *et al.*, 2003), and are by far the most popular (see Wheatcroft, 1990, for an alternative approach). Although the assumptions underlying such models are simplistic (symmetric small-scale particle displacement; Solan *et al.*, 2004), they have proven empirically valuable (Meysman *et al.*, 2003) and are therefore widely used to quantify and compare rates of sediment mixing between different areas (Solan *et al.*, 2004; Reed *et al.*, 2006). Bioturbation coefficients (Table 1) were calculated by Kohl and Martin (1999) for the first 10 months of the study using the following formula:

$$C_t = C_0 \exp(-z \times \text{depth})$$

where

C_t = bead count at time t ;

C_0 = initial bead count;

$z = v/D_b$;

v = sedimentation rate;

D_b = biodiffusion coefficient (cm² yr⁻¹); and depth is in cm.

Sedimentation rate (v) was determined from a core taken in 1998 adjacent to the low marsh plot by Nikitina *et al.* (2000). They reported a rate of 2.9 ± 0.3 mm yr⁻¹ for the last 100 yr. This rate was considered quite conservative since it is in agreement with other calculated local sediment rates and with the reported sea-level rise in the area. Therefore, we used this rate for all three plots to determine D_b . The term 'sedimentation rate' is, however, somehow imprecise and accounts for both autocompaction and vertical marsh accretion (Cahoon *et al.*, 1995; Goodman *et al.*, 2007). In fact, autocompaction, where peat occurs, can take values of the same order as tide-level change (Cahoon *et al.*, 1995; Allen, 2003) and has been calculated close to 1 mm yr⁻¹ in Wolf Glade (Southern Delaware; Pizzuto and Schwendt, 1997). Thus, we will refer to burial rate when describing the vertical displacement of the bead layers relative to the sediment–water interface (SWI) (see Meysman *et al.*, 2005, for terminology regarding sedimentation, sediment accumulation, etc.).

Depth in equation (1) represents the mixed-layer thickness, which is the region adjacent to the sediment–water interface in which biological and physical sediment displacement occurs. An accurate knowledge of the vertical extent of the mixing layer and whether it varies in space or time is important in determining the likelihood that a signal will be destroyed before it can be buried and preserved beneath the mixed layer (Wheatcroft and Drake, 2003).

Results and discussion

Seasonal profiles

Profiles of large and small beads parallel one another in all plots, indicating little if any size selectivity by bioturbators (Fig. 2); bead sizes will therefore not be differentiated further in this study.

The high marsh is characterised by a very rapid reduction downcore of red bead abundances (spread in November 1997) through June 1998, i.e., for a period of <7 months (Fig. 2). During this period, sediment mixing appears to have been negligible and the beads remained concentrated at the SWI. After another month (by July 1998), however, bead concentrations peaked beneath the SWI at 1–2 cm. Based on the subsurface peak, a burial rate of ~12 mm yr⁻¹ is estimated for the period (8 months); however, burial was not continuous and instead occurred mostly between June and July, so that the actual annualised rate is >8 mm yr⁻¹ (Fig. 2). By September (1998), the red peak had broadened upward somewhat toward the SWI, although the subsurface peak persisted. In contrast to the red layer, there was no significant increase in dispersion of the yellow bead layer between July 1998 (when yellow beads were spread) and September 1998,

Table 1 Bioturbation coefficients (D_b ; cm² yr⁻¹) for total tracers; ranges are given in parentheses (from Kohl and Martin, 1999)

	February 1998	June 1998	July 1998	September 1998
High marsh	0.06 (0.06–0.08)	0.08 (0.08–0.09)	0.38 (0.06–0.69)	0.44 (0.07–0.54)
Intermediate marsh	0.41 (0.35–0.41)	0.41 (0.38–0.57)	0.44 (0.13–0.50)	0.41 (0.17–0.66)
Low marsh	1.20 (1.10–1.55)	0.66 (0.60–0.69)	1.29 (1.10–2.18)	0.47 (0.17–3.15)

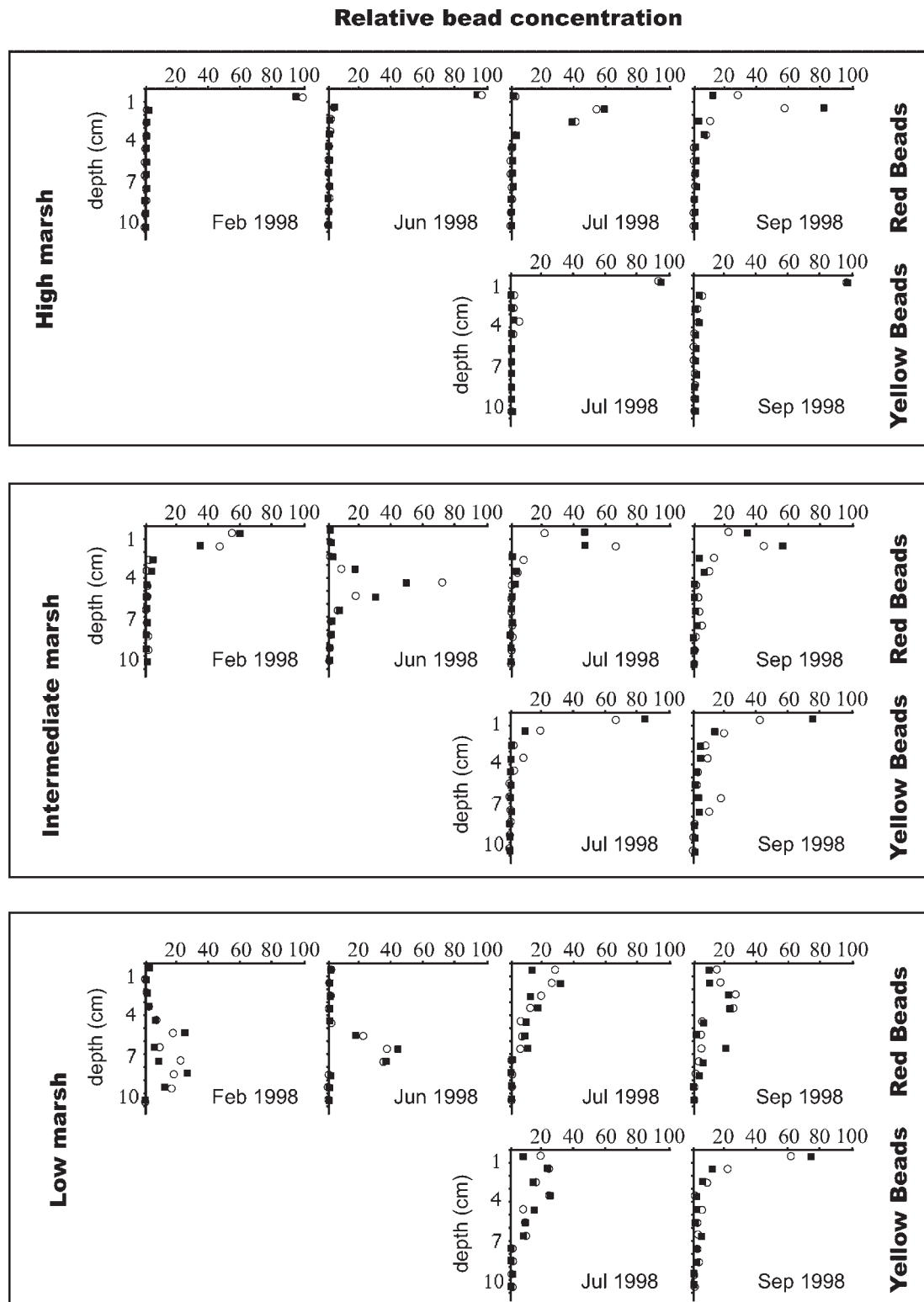


Figure 2 Seasonal bead distributions at high, intermediate and low marsh plots for red and yellow bead tracers; X-axes represent relative bead concentration versus depth (cm). Black squares, large beads; circles, small beads

indicating that sediment mixing occurred mainly in late spring and early summer.

The intermediate marsh profiles resemble those of the high marsh but sediment mixing was more intense than in the high marsh (Fig. 2). In contrast to the high marsh, the red layer was smeared downward slightly more in the intermediate marsh by February 1998. Smearing of the red layer continued into June (down to at least to 7 cm), with the red peak occurring at ~4–5 cm, yielding an approximate burial rate of 64 mm yr^{-1} .

The red bead concentration peak appears to have shifted upward in July and September, similar to the low marsh plot. Furthermore, the yellow layer (spread on July) remained relatively intact into September in the intermediate marsh plot, similar to the high marsh.

In the low marsh plot, concentration peaks were less distinct than in the high and intermediate marsh plots. The behaviour of the bead profiles in the low marsh plot suggests that physical sedimentary processes shape the bead profiles until June, after

which bioturbation becomes more prominent. Low marsh red profiles were already smeared downward to 5–10 cm by February (i.e., winter, when bioturbation should have been minimal) (Fig. 2), suggesting enhanced sediment resuspension/redeposition during tidal flux/flushing due to the lower elevation in the marsh with respect to the tidal frame. This effect, although to a lesser degree, is also present in the intermediate marsh. In late January and early February 1998, two of the largest northeasters on record also affected the region and most likely resuspended and redeposited sediment most intensely in the low marsh. Rooth and Stevenson (2000) reported that the storm surge doubled the water level (from an average of 38 cm to 71 cm) and the hydroperiod for nearly a week along the eastern shore of Chesapeake Bay in Maryland. Orford *et al.* (1996) suggested that extreme surges import coarser material to the marsh and that they can remove finer material, which may be transported back to the marsh during fair-weather conditions. Resuspension and removal of sediment between February and June 1998 has been described for similar marsh environments of Chesapeake Bay, demonstrating the importance of winter storms in promoting burial over short periods, but the role of storms in long-term marsh accretion is poorly understood (Rooth and Stevenson, 2000; Van de Plassche *et al.*, 2006). In June 1998 red beads remained buried at ~5–8 cm in the low marsh. Downward dispersion of the red profiles in the low marsh was accompanied by downward smearing of the yellow profiles by July, when the activities of burrowing invertebrates and macrophyte root growth increased. However, the red profiles appeared to shift upward in July and September, followed by yellow profiles in September.

The upward smearing of bead profiles, particularly in the intermediate and low marsh plots, may reflect the spatiotemporal variability in sampling and, especially, the seasonality of bioturbation. Bioturbation rates (parameterised by the biodiffusion coefficient D_b) tended to be lowest within the high marsh ($<0.7 \text{ cm}^2 \text{ yr}^{-1}$) and increased into the low marsh (up to $3.2 \text{ cm}^2 \text{ yr}^{-1}$). Rates also tended to increase in all plots in late spring and early summer (between June and July; Table 1), when biological activity of invertebrates and macrophytes is greatest (Duport *et al.*, 2007). Bombay Hook D_b values (Table 1) lie within the lower range of calculated bioturbation rates ($0.001\text{--}250 \text{ cm}^2 \text{ yr}^{-1}$) of other biologically active sedimentary environments (Aller, 1982; Solan *et al.*, 2004; Wheatcroft and Drake, 2003); in these environments, rates below $10 \text{ cm}^2 \text{ yr}^{-1}$ correspond to winter values, and are reported mainly from the eastern seaboard of the USA (Wheatcroft and Drake, 2003) or deep-sea sediments (Hippensteel *et al.*, 2000). D_b values reported here are two orders of magnitude below most rates reported for shallow subtidal sediments ($\sim 30 \text{ cm}^2 \text{ yr}^{-1}$; Aller, 1982). These values may be similar to those of more northerly marshes. Although no sediment mixing studies have been performed in these northerly salt marshes, several authors have hypothesised that bioturbation should be less pronounced in marshes from Connecticut to Nova Scotia, possibly in response to the influence of climatic factors on bioturbation rates (Saffert and Thomas, 1998; Horton and Murray, 2006; Goodman *et al.*, 2007).

Seven-year profiles

We revisited the sites after 7 years to evaluate how the seasonal profiles were further incorporated into the sediment and the implications for high-resolution sea-level studies.

The 7-yr profiles derived from the red and yellow beads remained largely unchanged for the high, intermediate and low marsh, respectively. Red and yellow profiles were paralleled by green bead profiles, which were spread in September 1998, but not sampled until April 2005 (Fig. 3). Thus, it appears that after an initial interval of relatively intense reworking, the bead concentrations reached an approximate equilibrium profile characteristic of each plot (elevation).

Nevertheless, the plots exhibit distinct profiles. In the high marsh, all profiles (red, etc.) are very similar, most likely because dense macrophyte root systems inhibit bioturbation (Hippensteel *et al.*, 2002). In this plot, the maximum mixed-layer thickness is $\sim 5 \text{ cm}$, although most beads are concentrated in less than 3 cm. Distinct bead maxima (peaks) are recognisable at $\sim 4\text{--}6 \text{ cm}$ depth within the cores. These bead peaks provided an average ($n=12$) burial rate of 6.2 mm yr^{-1} for the study period ($\sim 7 \text{ yr}$) (Table 2). As expected, the bead layers were smeared downward more intensely in the intermediate marsh plot and the profiles were more heterogeneous than in the high marsh; i.e., mixing is 'lumpy' in the intermediate marsh, probably because root systems are patchier (Hippensteel *et al.*, 2000; compare cores A and B, Fig. 3). The maximum mixed-layer thickness in the intermediate marsh was $\sim 9 \text{ cm}$, peak concentrations occurred between 3 and 7 cm depth and average burial rate was 5.8 mm yr^{-1} , which is fairly similar to the rate obtained in the high marsh (Table 2).

Nevertheless, the low marsh profiles exhibited the most heterogeneous profiles of all plots (Fig. 3). The mixed-layer thickness in the low marsh was greatest in core A ($\sim 13 \text{ cm}$), whereas in core B the mixed-layer was somewhat smaller ($\sim 8 \text{ cm}$) and distinct concentration peaks remained evident, providing an estimated burial rate of $\sim 10 \text{ mm yr}^{-1}$ ($n=6$). In all cores (except core A, low marsh, where intense mixing prevented differentiation of the tracer profiles), red and green bead peaks are clearer than those for yellow beads. The tendency for greater dispersion of yellow profiles may have resulted from rapid bioturbation immediately after the yellow layer was spread in July 1998 (see above). Red and green layers were spread when bioturbation was presumably less intense, allowing greater time for initial burial of the layers before intense bioturbation and dispersion could occur. This inference is supported by the spacing between peaks of different colours: $\sim 2 \text{ cm}$ between red and green peaks for cores in the high marsh, $\sim 3\text{--}5 \text{ cm}$ in the intermediate marsh, and $\sim 2 \text{ cm}$ for core B in the low marsh, while yellow profiles are typically less distinct (Fig. 3).

The burial rates derived from the 7-yr profiles for the high and intermediate marsh plots (Table 2) approximate: (1) sedimentation rates for all Delaware marshes (range $2.0\text{--}7.7 \text{ mm yr}^{-1}$; Kim *et al.*, 1997, 2004; Nikitina *et al.*, 2000) and (2) sedimentation rates of marshes along the mid-Atlantic coast of the USA ($1.4\text{--}7.9 \text{ mm yr}^{-1}$; Stevenson *et al.*, 1985; Sharma *et al.*, 1987; Carson *et al.*, 1988; Ward *et al.*, 1998). The differences in the rates derived by the different methods are considerable and are most easily related to the time span that they cover; for instance, short-term sedimentation rates (i.e., spanning $\sim 1\text{--}10 \text{ yr}$) tend to be higher than long-term rates (i.e., $>50 \text{ yr}$). The differences might relate to the frequency of flooding; many small frequent pulses or larger less frequent pulses such as storms may promote burial (Bentley *et al.*, 2006). Furthermore, there is significant interannual variation in sedimentation that is controlled by the complex interactions among sea-level variations, hydroperiod, marsh vegetation and sediment budget (e.g., Morris, 2006). In fact, short-term sedimentation rates based on artificial tracers (i.e., marker horizons) analysed in other areas yield comparable or even greater values than those obtained here (up to 24 mm yr^{-1} ; Callaway, 2001). This might explain, in part,

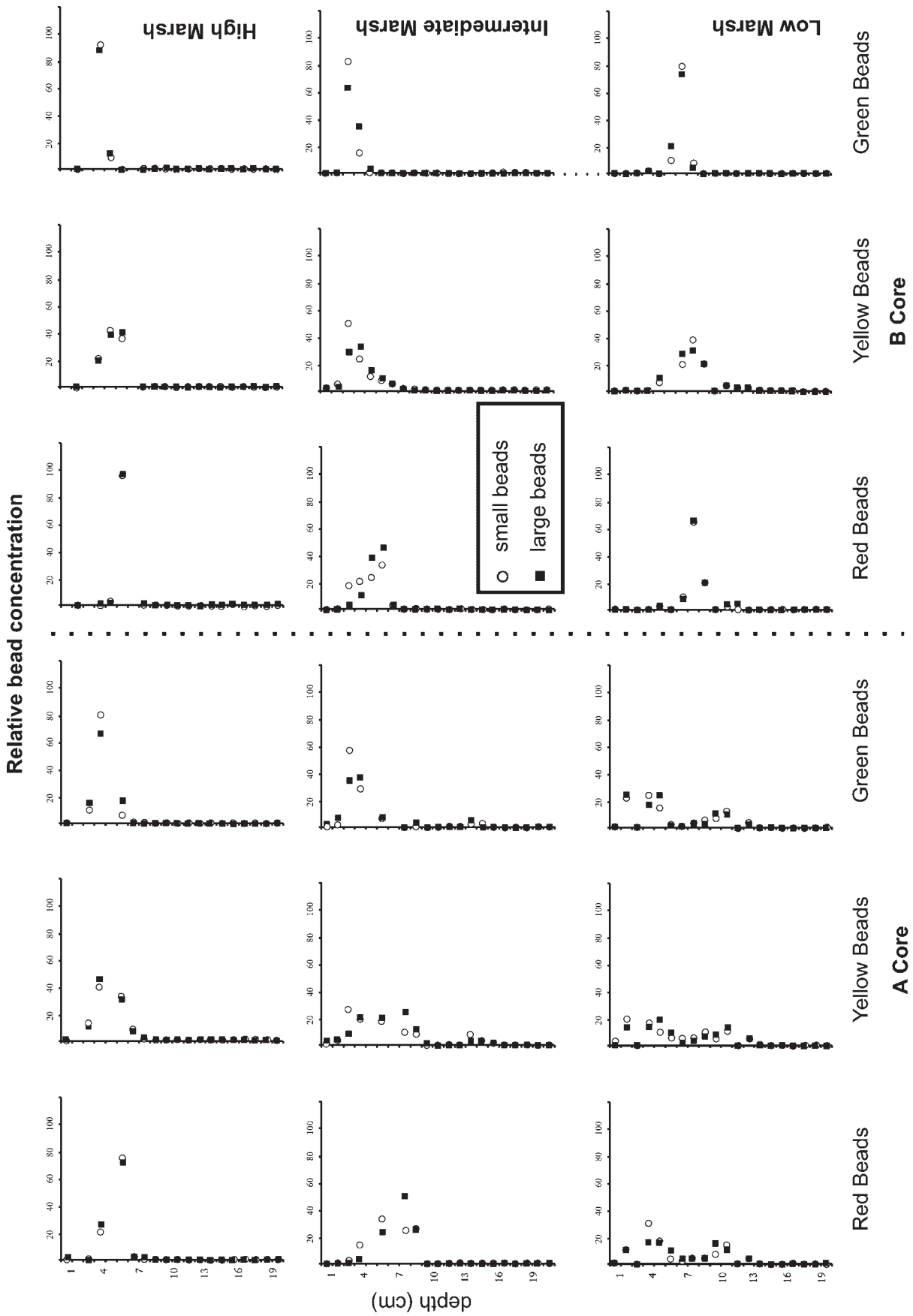


Figure 3 7-year bead distributions at high, intermediate and low marsh plots for red, yellow and green bead tracers versus depth (cm). Black squares, large beads; circles, small beads. Two replicate cores (A and B) are shown for each plot

Table 2 Seven-year burial rates for individual and total tracers (mm yr^{-1}); ranges are shown in parentheses. *n* represents the number of tracers used for calculations

	Red beads	Yellow beads	Green beads	Total
High marsh	7.4; <i>n</i> =4	5.9 (5.2–6.6); <i>n</i> =4	5.3; <i>n</i> =4	6.2 (5.2–7.4); <i>n</i> =12
Intermediate marsh	8.8 (7.4–10.1); <i>n</i> =4	3.7; <i>n</i> =2	3.8; <i>n</i> =4	5.8 (3.7–10.1); <i>n</i> =10
Low marsh	10.1; <i>n</i> =2	11.1; <i>n</i> =2	9.8; <i>n</i> =2	10.3 (9.8–11.1); <i>n</i> =6

the differences found when comparing longer-term (30 to >100 yr) sedimentation rates for Delaware based on ^{210}Pb and ^{137}Cs (range: 2.0–7.7 mm yr^{-1}) and burial rates based on bead experiments (range: 3.7–11 mm yr^{-1}).

Burial rates also appear to reflect bioturbation. When bead layer peaks are distinct, the spacing between layers implies burial rates of 4–20 times greater than those calculated for the 7-yr period and even more if compared to sedimentation rates. For example, up to 5 cm separate the green bead layer from the red bead layer in core A (intermediate marsh), implying a sedimentation rate of 67 mm yr^{-1} . These differences could be explained by upward or downward smearing by bioturbation. Thus, upward or downward transport by bioturbation can equal or exceed rates of sedimentation (see also Roberts *et al.*, 1997; Crusius and Kenna, 2007). Ironically, then, high burial rates in the low marsh appear to result more from bioturbation (i.e., sediment accumulation rates may primarily reflect sediment resuspension and redeposition within the system due to bioturbation rather than sediment transport into and out of the system).

Implications for sea-level studies

Physical and biological reworking within the mixed layer places bounds on the resolution of sea-level reconstructions. The mixed-layer thickness (range: ~5 to ~13 cm) reported here corresponds to the upper zone of root growth and oxygenation, zone of sulphate reduction, redox potential discontinuity and the decomposition of organic input from *S. alterniflora* (Howarth and Teal, 1979; Rhoads and Boyer, 1982; Lord and Church, 1983). Furthermore, it is similar to ranges reported in the literature for the mid-Atlantic coast of the USA (Sharma *et al.*, 1987; Koretsky and Van Cappellen, 2002; McCraith *et al.*, 2003; Koretsky *et al.*, 2005) and the worldwide average for marine environments of 9.8 ± 4.5 cm for the mixed layer thickness (Boudreau, 1998; Wheatcroft and Drake, 2003).

The greater mixed layer thickness of the intermediate and low marsh at Bombay Hook would be expected to decrease temporal resolution because of the greater residence times (transit time, Wheatcroft, 1990; i.e., the total time spent within the bioturbation zone) of sedimentary events (e.g., bead) layers before final burial beneath the mixed layer. For example, using an average sedimentation rate of 4 mm yr^{-1} for the low marsh, and a mixed-layer thickness of 13 cm, the calculated residence time would be >30 yr. This problem has been recently addressed by using non-traditional methodologies; e.g., subsurface samples of the entire mixed layer are used to produce analogues instead of surficial samples only (Patterson *et al.*, 1999; Hippensteel *et al.*, 2000, 2002; Martin *et al.*, 2002).

At Bombay Hook, the seasonal profiles provide evidence of relatively intense mixing due to physical and biological processes in the low marsh. In contrast, these processes are less pronounced in the high marsh. Based on these results, the high marsh is most suitable for high-resolution sea-level studies

because it is farthest removed from physical reworking and has the thinnest mixed layer (cf. equation (1)). On the other hand, the intermediate marsh plot is characterised by fairly well-preserved red and green bead layers in the 7-yr profiles, with a mixing layer thickness ranging from ~3 to 8 cm. From the point of view of sediment mixing, both marsh plots could be suitable for high-resolution sea-level reconstructions based on micro-palaeontological analysis.

The fact that sediment mixing due to bioturbation within the high and intermediate marsh plots occurs mainly in the late spring and early summer limits the potential time span of biological mixing. Indeed, Horton and Edwards (2003) and Horton and Murray (2007) concluded from a seasonal investigation of contemporary salt marsh foraminifera and their implications for sea-level studies that, if only one set of measurements can be obtained, sampling in the winter months may represent the most reliable alternative. In contrast, the low marsh plot is more likely to be subjected to physical reworking due to storms throughout the year. In fact, sea-level reconstructions based on low salt marsh peat are, by far, less accurate than high marsh when compared with tide-gauge data (Gehrels, 2000).

Further testing must be conducted in other locales because the results will potentially depend upon local ecological and taphonomic factors such as the depth of infaunal distributions and seasonal changes of porewater chemistry (Hippensteel *et al.*, 2000; Duport *et al.*, 2007). The possible influence of climatic factors on bioturbation rates must be also considered. These factors are also strongly related to the tidal range. In microtidal settings, the apparent mixing-layer thickness seems to be lower than for macrotidal sites (Andersen *et al.*, 2000). On the other hand, micro- and mesotidal marshes are more likely to be influenced by storm events (French, 2006). Episodic or periodic (e.g. seasonal) variations in the burial rate can potentially accentuate or destroy the geological signal (Bentley *et al.*, 2006; Van de Plassche *et al.*, 2006). Furthermore, long-term (>50 yr) changes of marsh elevation are determined by mean high water (MHW) level, in which the low marsh accumulates relatively quickly, while the high marsh remains in 'equilibrium' with MHW (Temmerman *et al.*, 2004; Goodman *et al.*, 2007). Although sea-level rise and marsh accretion are not exactly in balance, microtidal marshes like those of Delaware generally lie close to the hypothetical equilibrium state (French, 2006), and thus are potentially more suitable for high-resolution sea-level studies.

Conclusions

Field experiments involving artificial layers of glass beads placed in low, intermediate and high marsh plots of Delaware marshes yield estimates of both bioturbation and burial rates. Bioturbation in Delaware marshes is relatively low for all three plots (D_b range 0.06–3.15 $\text{cm}^2 \text{yr}^{-1}$) and dominates between

June and July, although mixed layer thickness is large for intermediate and low marsh plots (≥ 10 cm). However, burial rates are rapid (range 3.7–11 mm yr⁻¹). This results in very good temporal resolution for the high marsh, preventing the low marsh from use in high-resolution sea-level studies.

These results are especially relevant for microtidal marshes like those of Delaware because large areas of these marshes lie closer to equilibrium with sea level and could provide higher-precision results. In these marshes bioturbation may be critical to the ability of such marshes to keep pace with sea level by resuspending sediment within the system that is later redeposited.

Acknowledgements Leorri was supported by a postdoctoral grant from the Basque Government (Spain) and by the Conseil Général of the Vendée (France). Dissertation research by Hippensteel and initial bioturbation studies by Kohl and Martin were supported by NSF Grant No. EAR-9614155. Horton was supported by NSF Grant No. (EAR-0713332). We thank Nieves González for carrying out sampling preparation and bead counting and Katherine Skalak for performing the topographic survey. We also thank Prof. Gehrels and Prof. Shennan for their comments and suggestions, which greatly improved the original manuscript.

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