



# Salt Marsh Migration into Lawns Revealed by a Novel Sediment-Based Approach

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## Abstract

Upslope migration will be critical to the future survival and stability of tidal salt marshes in an age of accelerated sea-level rise, yet only a small number of studies have measured historic migration rates. We developed a new approach for reconstructing salt marsh migration that can be used even in situations where that migration would be undetectable by aerial photograph analysis, such as the growth of marsh plants under trees or the movement of marsh ecosystems into mowed lawns. Our approach involves identifying a wedge of salt marsh peat (overlying the pre-existing upland soil) through the presence of foraminifera and then dating that wedge using <sup>137</sup>Cs. We demonstrate our approach by calculating migration rates (1963–2016) for two lawn-adjacent salt marshes along the Connecticut coast of Long Island Sound. Both marshes showed substantial migration over this time period, although vertical migration rates differed dramatically between the two sites, perhaps because of the differential influence of large storms. Further, we demonstrate that the presence of foraminifera (an unequivocal signal of tidal inundation) constitutes a more accurate indicator of the migration wedge than high organic content. Our relatively inexpensive approach could be used to assess migration rates at multiple sites in order to better understand the factors controlling marsh migration.

**Keywords** Foraminifera · Wedge · Invisible migration · Sea-level rise · Long Island Sound

## Introduction

Salt marshes provide habitat, wave attenuation, and recreational opportunities, all of which are especially valuable in urbanized estuaries such as Long Island Sound (LIS). While relative sea-level rise (RSLR) threatens salt marshes with the potential for submergence at the seaward edge (e.g., Schultz et al. 2016; Roman 2017), it also provides an opportunity for

marshes to expand laterally at the upslope edge (Fagherazzi et al. 2019). Upslope migration will be critical in determining the fate of salt marshes over the next few decades (Schuerch et al. 2018), especially where limited sediment supply hinders accretion. Marsh migration can also contribute to an increase in carbon sequestration (Rogers et al. 2019).

While the process of marsh migration was described conceptually by Brinson et al. (1995), we still know relatively little about historic and current rates of marsh migration. The paucity of data on migration rates limits our ability to answer important questions such as the following (Fagherazzi et al. 2019): Is migration proceeding at roughly the rate expected from RSLR, or is the resilience of upland ecosystems slowing the process? How do slope and land cover affect migration rates? What is the role of large storms in driving migration? How does the areal rate of migration compare to that of marsh submergence?

A dominant approach to measuring salt marsh migration has been comparing historic and modern marsh extents using maps, aerial photographs, and/or satellite images. Studies from Florida (Raabe and Stumpf 2015), Chesapeake Bay (Schieder et al. 2018), and Delaware Bay (Smith 2013) used this approach to demonstrate that marshes have migrated landward into surrounding forests over the past 80–160 years at

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substantial rates, sometimes exceeding the rate expected from RSLR. However, using a similar approach, Field et al. (2016b) found no evidence for net landward migration of the marsh–forest boundary over the period 1974–2010 using aerial photographs from the Connecticut shore of LIS. While this inconsistency may reflect real ecological differences among regions and sites, it may also reflect limitations of the approach.

The approach used in these studies is a powerful way of looking back in time, but it suffers from some unavoidable shortcomings, including the poor resolution of some historic maps and photographs, as well as the limited time span over which these records are available. More importantly, this approach relies on being able to accurately distinguish, in an aerial image, between the tree canopy of a forest and the herbaceous cover of a marsh, which means that it cannot detect two specific cases of marsh migration: marsh plants migrating upslope under the forest canopy and marsh plants migrating into non-wooded landscapes, such as lawns. The latter is particularly relevant for an urbanized estuary like LIS, where marsh-adjointing areas are often mowed to improve views. Many of these lawns continue to be mowed even as marsh plants replace lawn grasses (Anisfeld et al. 2016a), making it nearly impossible to accurately determine the marsh–lawn boundary from the air.

Besides aerial photography, field-based methods have also been used to document marsh migration. Some studies have used repeated field measurements to assess changes over time in the health of upland plants (e.g., absence of recruitment, increased water stress, elevated mortality) and their replacement by halophytic vegetation (Williams et al. 1999; Williams et al. 2003; DeSantis et al. 2007; Wasson et al. 2013), although this requires concentrated effort at one site over a long time period. In addition, tree-ring analysis has been used to reconstruct the growth rates of coastal forests over time and assess their response to SLR and/or coastal storms (Field et al. 2016b; Fernandes et al. 2018), although this approach does not directly measure upslope movement of marsh into the forest.

A different approach was taken by Hussein (2009), who assessed marsh migration over the last two millennia at two Chesapeake Bay marshes by determining the thickness and age of organic horizons (i.e., marsh peat) overlying buried mineral surfaces (i.e., pre-existing upland soil). However, the use of organic matter (OM) as a salt marsh proxy is potentially problematic, both because other environments can accumulate high-OM sediment (e.g., freshwater wetlands) and because marsh migration can lead to OM enrichment of the underlying mineral soil through downwards root penetration and slowed decomposition rates, thus altering and obscuring the original mineral soil surface.

We present an alternative approach that addresses some of the shortcomings outlined above. Our approach is similar to that of Hussein (2009), except that we use a salt marsh indicator that is specific to the marine environment, responds

rapidly and predictably to changes in flooding regime, and does not propagate downwards to a significant extent, namely, the presence of fossilized foraminifera. Salt marsh foraminifera are epifaunal or shallow-infaunal microorganisms that live only below the upper limits of tidal inundation and whose agglutinated or calcareous tests are preserved in large numbers in salt marsh sediment (e.g., Scott and Medioli 1978).

In this work, we use the presence of foraminifera to identify the sedimentary signature of marsh migration. Our research asks three questions: (1) Can foraminifera be used to quantify migration rates? (2) How does the presence of foraminifera compare to high organic content as a marker of salt marsh sediment? (3) Is migration of marshes into lawns occurring in LIS?

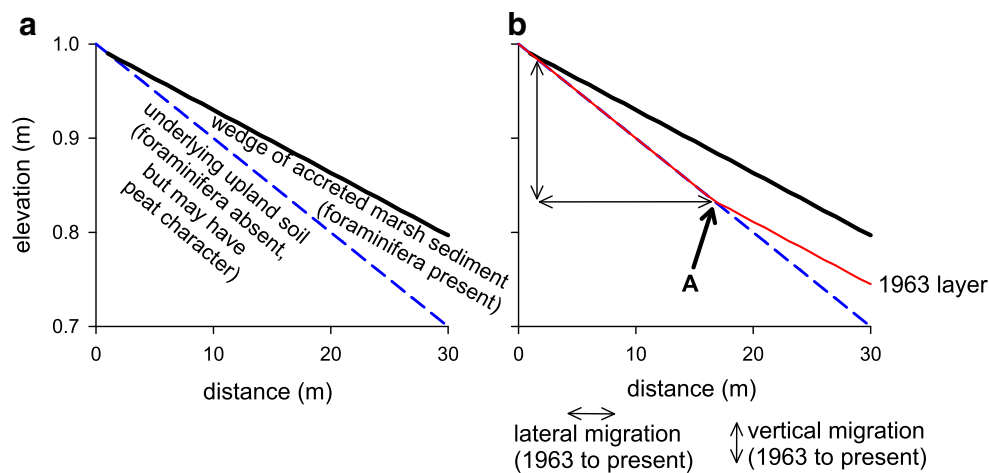
## Methods

### Approach and Study Sites

To illustrate our approach, we examine the signature that would be left in the coastal stratigraphic record by a hypothetical salt marsh migration scenario (Fig. 1). For this scenario, we assume that the marsh is migrating over a pre-existing upland (slope of 1%) at a horizontal rate of 0.3 m year<sup>-1</sup> (corresponding to a vertical migration rate of 3 mm year<sup>-1</sup>, roughly the same as the recent multi-decadal rate of RSLR in LIS). We further assume that as soon as the upland is converted to salt marsh, it starts to accrete vertically, but at a relatively low rate of 1 mm year<sup>-1</sup> given its infrequent inundation. (For example, running Jim Morris's Marsh Equilibrium Model (<http://129.252.139.226/model/marsh/mem2.asp>) with default settings and an initial marsh elevation set to MHW produces an accretion rate of 0.7 mm year<sup>-1</sup>).

These assumptions result in a wedge of salt marsh sediment overlying the upland soil (Fig. 1a): locations that are farther downslope have had longer to accrete, so they have a thicker unit of salt marsh sediment, while locations near the migration front have only a thin salt marsh layer. If our hypothetical scenario is correct, then this wedge signature should exist in the coastal stratigraphic record beneath the modern marsh–upland transition zone. It should also be readily identifiable if we use an appropriate indicator, such as preserved foraminifera, to reliably distinguish salt marsh sediment from upland soil.

Once the wedge is identified, it can also be dated. We focus on a relatively simple dating approach utilizing the 1963 peak in the atmospheric deposition of <sup>137</sup>Cs from nuclear testing. The advantages of <sup>137</sup>Cs dating in this context include the ability to rapidly date multiple cores by focusing in on the appropriate depths, as well as the ~50-year time scale, which covers a period of relatively rapid RSLR that would be expected to trigger measurable marsh migration. Few other



**Fig. 1** Schematic illustration of the hypothetical marsh migration scenario described in the text. **a** Thick solid line represents current marsh surface; dashed line represents buried pre-existing upland surface. The point where the two meet is the current marsh–upland boundary. Elevation and distance are both relative to arbitrary points. Vertical scale

chronological methods can as reliably and easily identify a stratigraphic horizon from a specific year. Therefore, we negate the need to factor large chronological uncertainties into our interpretation, as would be necessary if the sediment was dated using other methods, such as radiocarbon dating.

Using the assumptions above, we can illustrate how the sediment surface would have looked in 1963. At that time, marsh migration had proceeded to point A (Fig. 1b), so upslope of point A,  $^{137}\text{Cs}$  was being deposited on upland soil, while downslope of point A,  $^{137}\text{Cs}$  was being deposited on the marsh surface. Given that the marsh then continued migrating and accreting on top of that  $^{137}\text{Cs}$  layer, point A (the 1963 marsh–upland boundary) can be retrospectively identified by finding the location where the  $^{137}\text{Cs}$  layer shifts from being at the base of the marsh sediment to being in the middle of the marsh sediment. The lateral and vertical extent of marsh migration since 1963 can then be calculated as the distance (laterally and vertically) from point A to the current marsh–upland boundary. Since tide-gauge records are available for LIS over the same time period, these ecological trends can be compared to prevailing rates of RSLR.

To test this approach and use it for quantifying migration rates, we sampled one transect at each of two marshes along the Connecticut shore of LIS: Sherwood Island State Park in western LIS and Hammonasset Beach State Park in central LIS. Using the Cahoon et al. (2009) geomorphic classification system, both marshes would be considered Estuarine Embayment–Stream Channel Wetlands. Sherwood has been the site of previous studies of marsh accretion (Anisfeld et al. 2016b), herbivory and marsh submergence (Schultz et al. 2016), and the marsh–upland ecotone (Anisfeld et al. 2016a). Hammonasset was chosen because it is a contrast to Sherwood in its geographic position (farther east), tidal range

is exaggerated by 100× relative to horizontal scale. **b** As in **a**, with the addition of a thin line representing the 1963  $^{137}\text{Cs}$  layer. Point A represents the marsh–upland boundary in 1963. From 1963 to the present, the marsh has migrated over the distances shown

(larger), and marsh-to-upland slope (higher). Both marshes were included in Field et al.’s (2016b) analysis, though their marsh–forest transects were in a different part of the marsh from our marsh–lawn transects.

Our transects extended downward from the upland into the high marsh; in both cases, the upland in question consisted of a lawn that was mowed periodically by park staff. Vegetation along the transects transitioned gradually from upland grasses (e.g., *Festuca* spp., *Panicum* spp., *Poa* spp.) to high marsh plants (*Juncus gerardii*, *Iva frutescens*, *Solidago sempervirens*, *Spartina patens*, *Distichlis spicata*).

### Sampling and Analysis

We measured surface elevations, relative to local benchmarks, every 0.1–0.2 m laterally along each transect using a total station or a laser level. Benchmark elevations were measured relative to the North American Vertical Datum of 1988 (NAVD88) using an RTK-GPS system. We collected local tidal hydrology data at each site using Onset water-level loggers (6-min frequency, deployed for at least 15 months at each site) and correlated our data to nearby NOAA tide gauges (Bridgeport for Sherwood; New Haven Harbor for Hammonasset; correlations available in Online Resource Figures A and B). Following the approach described in Anisfeld et al. (2016), we used these correlations to create a synthetic high-tide dataset for the period 2007–2016 for each site, and calculated the elevations corresponding to mean higher high water (MHHW) and to flooding frequencies of 1%, 5%, and 10% over this time period.

Surface sediment samples (0–1 cm) were collected at varying distances along each transect to identify the transition point from salt marsh (foraminifera present) to upland

(foraminifera absent). Based on the results from surface sampling, cores were collected at varying distances along each transect (and to varying depths) to accurately and efficiently establish the position of the hypothesized wedge. Cores ranged in depth from 3 to 13 cm and were collected using a knife and then sectioned into 0.5- or 1-cm increments. A total of 20 cores were collected and analyzed (eight at Sherwood, 12 at Hammonasset), of which one was collected in 2015, 13 in 2016, and six in 2017. When calculating migration rates, we used 2016 as the collection date for all cores.

Sediment samples—both surface samples and core sections—were preserved in ethanol (25%). Before analysis, samples were wet-sieved and the retained 63–500- $\mu\text{m}$  fraction was divided into two sub-samples. One sub-sample was weighed wet, dried at 60 °C, and re-weighed to allow conversion from wet to dry weights. This sample was later ground to a fine, homogenized powder and used for two further analyses (on separate aliquots): organic matter and  $^{137}\text{Cs}$ . Organic matter (OM) was measured by loss on ignition in a muffle furnace at 500 °C for 12 h, and  $^{137}\text{Cs}$  activity was counted on a high-purity germanium gamma counter using the methods and instrument described in Anisfeld et al. (2016b). Roots and rhizomes larger than 500  $\mu\text{m}$  were not included in the OM and  $^{137}\text{Cs}$  analysis to avoid directly sampling relatively young material that had penetrated downwards into older layers.

The second sub-sample from the sieving was weighed wet, stored at 4 °C, and later counted for foraminifera. Specifically, the sample was re-suspended in water and examined under a binocular microscope to count the number of foraminifera present (including both dead and living at the time of sampling, i.e., the total assemblage). Foraminiferal abundance was expressed as number per dry gram of sediment; values ranged from 0 to 12,800. However, our analysis focused primarily on presence/absence, where samples with 8 or fewer foraminifera per dry g were classified as absent. This threshold was selected because it corresponded to a count of approximately 2–3 foraminifera in a sample, which was considered low enough that it did not represent a viable population, but rather a small amount of contamination (e.g., from down-core mixing, or the presence of allochthonous tests).

Eleven haphazardly selected samples were split into replicate pairs in the lab and analyzed for foraminifera. We also collected one pair of field replicates (two samples collected from the same location). For these 12 replicates, foraminifera were either present in both replicates (8 pairs) or absent (4 pairs); there were no pairs for which foraminifera presence/absence differed between the replicates.

### Calculating Migration Rates

For each transect, we identified the highest elevation at which foraminifera were present in the surface samples, referred to as

the highest occurrence of foraminifera (HOF; Wright et al. 2011). We took great care to identify the HOF as precisely as possible, by iteratively taking samples until we honed in on the boundary between the HOF and the lowest elevation with foraminifera absent. Since the resulting uncertainty in HOF was small (< 3 mm vertically) compared to other sources of uncertainty, we did not account for it in our calculations.

For each core, we identified the maximum depth at which foraminifera were present, which we refer to as the lowest foraminiferal depth (LFD) and define as the bottom boundary of the sedimentation wedge. We did this by iteratively analyzing sections until we honed in on the boundary between the deepest sample with foraminifera present and the shallowest sample with foraminifera absent. For example, if foraminifera were present in the 3–3.5-cm section (and above it), but not in the 3.5–4-cm section (and below it), the LFD was 3.5 cm.

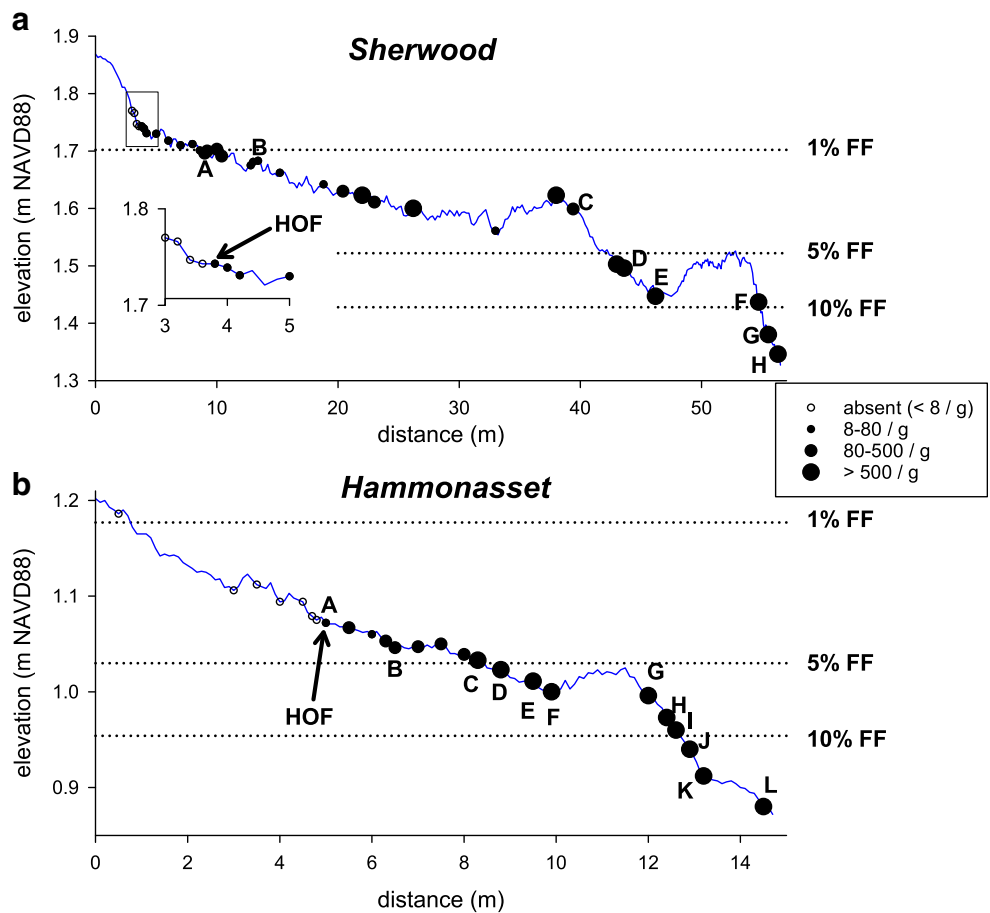
We used our  $^{137}\text{Cs}$  data to quantify migration rates by locating the point where the  $^{137}\text{Cs}$  layer shifted from being at the base of the marsh sediment to being in the middle of the marsh sediment (point A in Fig. 1b). We first identified the  $^{137}\text{Cs}$  layer for each core, defined as the depth range containing the  $^{137}\text{Cs}$  peak (which varied from 1 to 3 adjacent core sections; Online Resource Figures C and D), and determined whether it fell above or below the LFD. We then identified the two cores in each transect that sandwiched point A: the highest-elevation core where the  $^{137}\text{Cs}$  layer was above the LFD, and the lowest-elevation core where the  $^{137}\text{Cs}$  layer was at or below the LFD. The LFDs for these two cores constitute our range of estimates for the location of the marsh–upland surface boundary in 1963 (point A). The distances (vertical and lateral) from these LFDs to the HOF constitute our range of migration estimates over the period 1963 to 2016.

## Results

Foraminiferal abundance in surface samples varied with elevation (Fig. 2), and both transects showed clear thresholds between environments in which foraminifera were present/absent. In particular, all surface samples seaward of 3.8 m (lateral distance from the start of the transect in an upland environment above marine influence) at Sherwood and 5.0 m at Hammonasset had foraminifera present, while landward of those points, all surface samples had no foraminifera (defined as < 8 foraminifera  $\text{g}^{-1}$ ). These foraminiferal thresholds (HOFs) occurred at elevations of 1.743 m and 1.072 m NAVD88 at Sherwood and Hammonasset, respectively, with corresponding flooding frequencies of 0.7% and 3.2% of all high tides over the period 2007–2016.

Cores generally showed abundant foraminifera near the surface and no foraminifera deeper in the core (Figs. 3 and 4), consistent with a transgressive trend of RSLR and

**Fig. 2** Surface elevation (thin line) and surface foraminifera samples (circles) at **a** Sherwood and **b** Hammonasset. Open circles indicate foraminifera are absent ( $< 8 \text{ g}^{-1}$ ), while filled circles indicate foraminifera are present, with increasing circle size indicating higher concentrations, as shown in the legend. The inset at Sherwood shows the eight highest-elevation foraminifera samples. Arrows point to the highest occurrence of foraminifera (HOF). Dashed horizontal lines indicate elevations corresponding to 1%, 5%, and 10% flooding frequency (FF) over the period 2007–2016. Letters indicate locations where sediment cores were collected

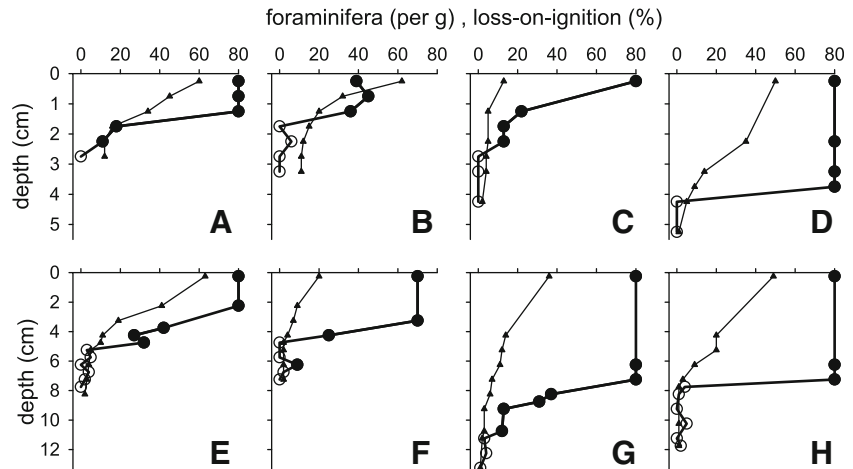


associated accumulation of salt marsh sediment over the pre-existing upland surface to fill the resulting accommodation space. There was a clear threshold separating presence and absence for each core (i.e., the LFD was well-defined). In only two out of our 20 cores was there any ambiguity: in core Sherwood F, the 6–6.5-cm section ( $9 \text{ foraminifera g}^{-1}$ ), which was just over our  $8 \text{ foraminifera g}^{-1}$  threshold and had two “absent” sections above it, was treated as absent, and in core

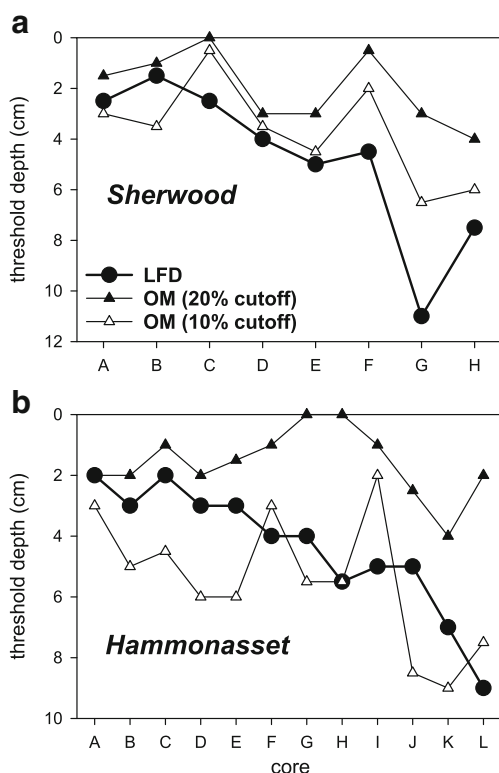
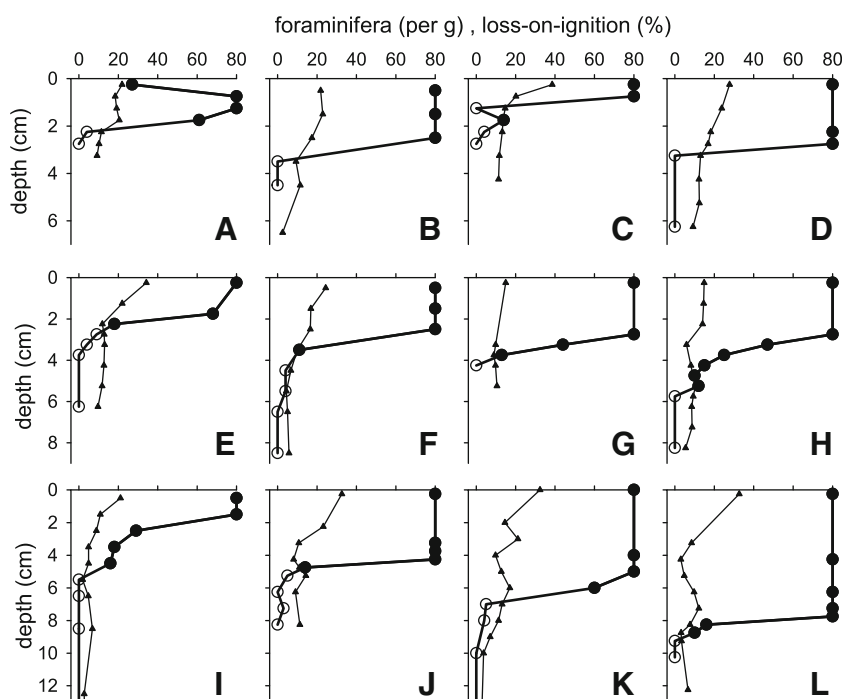
Hammonasset C, the 1–1.5-cm section, which had “present” sections above and below it, was treated as present.

The LFD varied from 1.5 cm (core Sherwood B) to 11 cm (core Sherwood G) and was generally deeper in cores collected at more seaward (lower-elevation) locations. A plot of LFD by core (Fig. 5) confirmed this pattern of deepening LFD at lower elevations, supporting the idea of a foraminiferal wedge (Fig. 1).

**Fig. 3** Foraminiferal abundance (large circles) and organic matter (small triangles) as a function of depth, for cores from Sherwood. Filled circles indicate foraminifera are present ( $> 8 \text{ g}^{-1}$ ), while open circles indicate foraminifera are absent. Foraminiferal abundance is cut off at 80 per g for ease of presentation, but ranged up to 12,800 per g. Note different depth scales in the two rows



**Fig. 4** Foraminiferal abundance (large circles) and organic matter (small triangles) as a function of depth, for cores from Hammonasset. Filled circles indicate foraminifera are present ( $> 8 \text{ g}^{-1}$ ), while open circles indicate foraminifera are absent. Foraminiferal abundance is cut off at 80 per g for ease of presentation, but ranged up to 7450 per g. Note different depth scales in the three rows



**Fig. 5** Threshold depths for cores from **a** Sherwood and **b** Hammonasset, using different thresholds: foraminiferal presence/absence, i.e., LFD (solid circles); OM above/below 20% (solid triangles); OM above/below 10% (open triangles). LFD consistently deepens at lower elevations (right side of graphs), while OM does not show a consistent pattern

In contrast, while OM also generally decreased with depth within a core, it did not show the well-defined threshold exhibited by the foraminifera (Figs. 3 and 4). Moreover, choosing arbitrary OM thresholds of 10% or 20% to define the marsh soil showed no pattern with position in the transect (Fig. 5), demonstrating that OM used in isolation is a poor means to identify the wedge of transgressive salt marsh peat overlying the pre-existing upland surface.

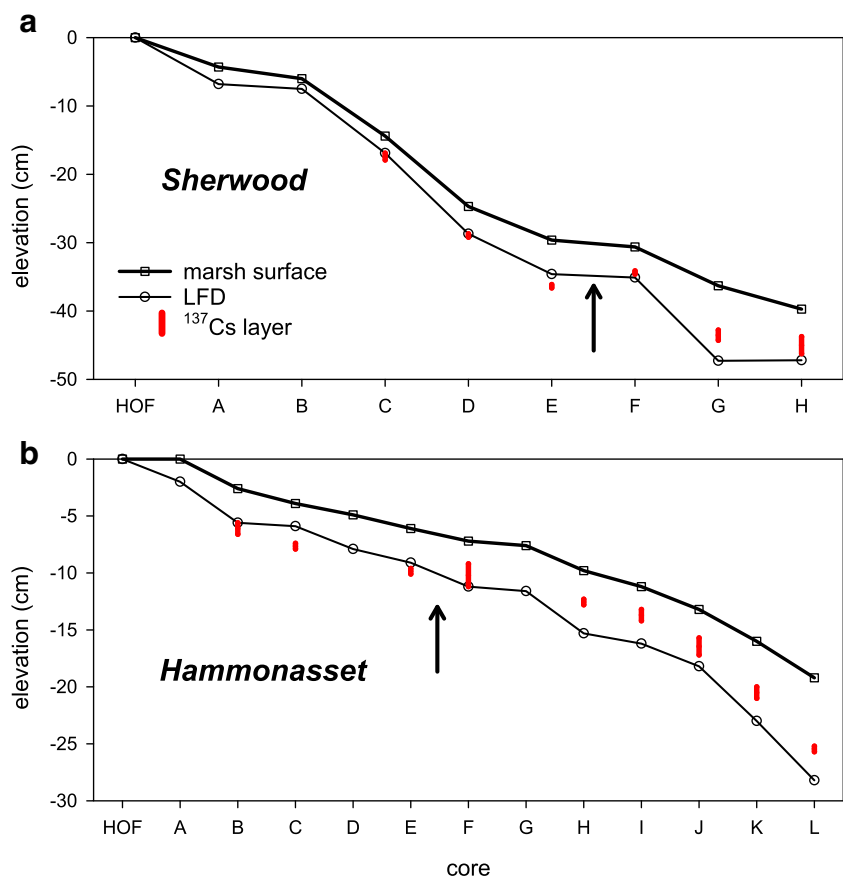
A plot of surface elevations and LFDs (Fig. 6) clearly illustrates the presence of a seaward-thickening wedge of foraminifera-containing sediment. In addition, as one moves seaward, the  $^{137}\text{Cs}$  layer shifts from at/below the LFD to above it. This transition point—which represents the upslope extent of foraminifera in 1963 (point A in Fig. 1b)—lies somewhere between cores E and F in both transects. Taking core E as the 1963 marsh extent provides a lower-bound estimate of migration rate, while using core F provides an upper-bound estimate. Total net horizontal migration (1963–2016) is estimated to be 42–51 m at Sherwood and 4.5–4.9 m at Hammonasset (Table 1), and vertical migration rates are 6.5–6.6  $\text{mm year}^{-1}$  at Sherwood and 1.7–2.1  $\text{mm year}^{-1}$  at Hammonasset.

## Discussion

### The “Foraminiferal Wedge” Method

Our method for measuring the historic rate of salt marsh migration utilizes preserved foraminifera to objectively and

**Fig. 6** Wedge diagram for **a** Sherwood and **b** Hammonasset. Elevations are plotted relative to the HOF (1.743 m NAVD88 at Sherwood and 1.072 m NAVD88 at Hammonasset). Squares represent the marsh surface; circles represent the LFD; and vertical lines represent the  $^{137}\text{Cs}$  layer. Arrows indicate transition points between  $^{137}\text{Cs}$  being above and below the LFD



reliably distinguish accreted salt marsh sediment from the pre-existing and underlying upland soil. Foraminifera are used extensively in relative sea-level reconstruction because distinctive assemblages occur at different tidal elevations, reflecting the preferences and tolerances for tidal inundation of taxa (e.g., Scott and Medioli 1978; Horton and Edwards 2006; Wright et al. 2011). Where these assemblages are preserved in the stratigraphic record, they can be used to reconstruct the pale-elevation of a former salt marsh surface relative to tidal datums through reasoning by analogy.

Here we use a simpler approach by merely distinguishing between sediment that contains foraminifera—and thus reflects marine influence—and sediment that does not. Since the preservation of high salt marsh foraminifera (which almost exclusively build agglutinated rather than calcareous tests) is typically good under conditions of RSLR and burial (Horton and Edwards 2006), absence of foraminifera in core material is taken to represent their absence at the time of sediment accumulation. This approach is relatively quick and inexpensive because it does not require taxonomic differentiation of tests. In addition, foraminifera are particularly suitable for identifying relatively short-term changes in salt marsh environments, such as the one in this study, because they are short-lived and respond quickly to changes in the frequency and duration of tidal inundation (e.g., Engelhart et al. 2013; Dura

et al. 2017), unlike plant communities or edaphic characteristics, which may take many years to fully develop (e.g., Craft et al. 2002; Anisfeld 2012).

The upper limit of foraminiferal habitat relative to the tidal frame (i.e., HOF) differed somewhat between our sites. At Sherwood, we identified HOF as occurring at 0.54 m above MHHW (corresponding to flooding frequency of 0.7%), compared to 0.30 m at Hammonasset (3.2% flooding frequency). Variability of HOF among sites likely reflects at least in part differences in tidal range, wind fields, and storm recurrence/magnitude that contribute to a given elevation being influenced by marine inundation to a greater or lesser degree. In a previous study, Wright et al. (2011) found that HOF at three sites in Connecticut occurred between 0.33 and 0.38 m above MHHW. The Wright et al. (2011) dataset was expanded by Kemp et al. (2015) using additional sites, primarily in western LIS and including Sherwood, where HOF was recorded at 0.39 m above MHHW. However, these previous studies had large vertical gaps (order of 5–10 cm) between HOF and the next highest sample and so may underestimate HOF. In contrast, our study focused specifically on identifying the HOF precisely (< 3 mm; Fig. 2).

An implicit assumption underlying our approach (as well as most uses of foraminifera in relative sea-level reconstruction) is that living foraminifera are epifaunal or shallow

**Table 1** Summary of parameters for the two transects

|   | Sherwood  | Hammonasset |
|---|-----------|-------------|
| Mean tidal range (m)  | 2.09      | 1.49        |
| MHHW (m NAVD88)   | 1.198     | 0.771       |
| HOF (m NAVD88)  | 1.743     | 1.072       |
| HOF flooding frequency (% of high tides, 2007–2016)             | 0.7       | 3.2         |
| Upper estimate of 1963 marsh boundary (LFD of core E; m NAVD88) | 1.397     | 0.981       |
| Lower estimate of 1963 marsh boundary (LFD of core F; m NAVD88) | 1.392     | 0.960       |
| Vertical migration, 1963–2016 (cm)                              | 34.6–35.1 | 9.1–11.2    |
| Vertical migration rate, 1963–2016 (mm year <sup>-1</sup> )     | 6.5–6.6   | 1.7–2.1     |
| Horizontal migration, 1963–2016 (m)                             | 42–51     | 4.5–4.9     |
| Slope of pre-existing upland surface (%)                        | 0.7–0.8   | 2.0–2.3     |

Mean tidal range was calculated using VDatum (<http://vdatum.noaa.gov>)

infaunal (top 0–1 cm). If a significant number of individual foraminifera are infaunal, then our estimates of LFD would be biased too deep by the downward movement of individuals. However, empirical studies demonstrate that while living foraminifera can occasionally be found at depths of up to ~ 50 cm, they are a typically an insignificant proportion of live individuals (e.g., Culver and Horton 2005; Milker et al. 2015), particularly in the marshes on the US northeast coast, including Connecticut (e.g., Saffert and Thomas 1998). We conclude that infaunal foraminifera are unlikely to result in misinterpretation of the salt marsh wedge. In addition, the clear presence/absence thresholds that we found both horizontally (HOF; Fig. 2) and vertically (LFD; Figs. 3 and 4) support the utility of our approach to assessing marsh migration.

In contrast to our foraminifera results, we did not find organic content to be a useful indicator for reconstructing the wedge of salt marsh sediment (Fig. 5). Instead, we found that cores from both ends of the transect showed a nearly continuous decline of OM with depth (Figs. 3 and 4). This type of vertical profile is a common one even for homogeneous marsh soils (e.g., Bricker-Urso et al. 1989; Anisfeld et al. 1999) and likely reflects increased decomposition in older, deeper materials, rather than deposition of an organic soil over a mineral surface.

Organic matter is unlikely to be a useful indicator for marsh migration studies because once marsh plants invade an area, their high root:shoot ratio (together with the reducing conditions caused by inundation) will lead to high belowground net OM inputs, overprinting and distorting the original signature of the underlying soil (Fig. 7). A similar process has been observed in constructed marshes (Craft et al. 2003). In the marsh–migration literature, this soil transformation process has been under-studied, though the salinization and alkalization involved in conversion of non-wetland soils to Histosols have received some attention (Gardner et al. 1992; Hussein and Rabenhorst 2001). Ignoring the downwards penetration of OM is likely to lead to errors in identifying the true extent of accreted marsh sediment. While these errors may be

less significant at long time frames—such as the 2000-year time frame used by Hussein (2009)—they are likely substantial for shorter-term, higher-precision analyses of recent marsh migration.

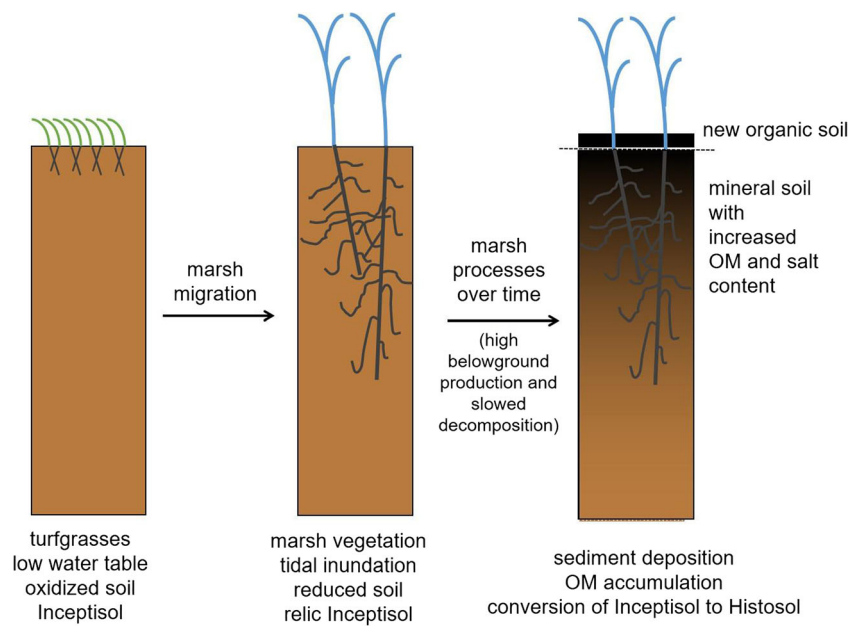
### Migration Rates

Over the next few decades, marsh submergence and erosion are expected to lead to large marsh losses, especially in locations with high RSLR and low sediment supply (Kirwan et al. 2010; Thorne et al. 2018), which could potentially cause the extinction of some marsh-dependent animals (Field et al. 2016a). Marsh transgression through upslope migration may compensate for marsh loss at the seaward edge, but the magnitude and rate of this process are uncertain (Horton et al. 2018; Schuerch et al. 2018; Fagherazzi et al. 2019). In LIS, Field et al. (2016b) found no evidence for marsh migration in sets of aerial photographs (1974–2010) from 37 sites (including both of our sites, but in different parts of the site). However, this analysis suffers from the limitations of aerial analysis discussed in “Introduction.” In particular, anecdotal evidence suggests that there may be two types of “invisible migration” (i.e. migration that cannot be reliably detected by analyzing aerial photos) taking place in LIS: salt marsh plants moving upslope under tree canopies and marsh plants invading mowed lawns.

Our study uses the foraminiferal wedge approach to measure the second type of “invisible migration,” namely, the conversion of upland lawns to marshes. We show that this migration is in fact happening, at least at the two sites where we looked for it. Leaving aside methodological differences, there are several possible explanations for the difference between our results and those of Field et al. (2016b). First, our study focused on lawns, which may provide a more conducive environment for migration than woodlands because of decreased shading and lower resilience to salinization (Anisfeld et al. 2016a). Second, different aspects of marsh structure and function may migrate at different rates; it is



**Fig. 7** Schematic illustration of the conversion of mineral soil to organic soil due to root in growth and slow decomposition



likely that foraminifera migrate more rapidly than marsh vegetation, the marsh indicator used by Field et al. (2016b). Although we did not quantify the proportions of marsh and upland vegetation along our transects, we did confirm that there were marsh plants within a distance of 0.5 m of the HOF at both sites. However, at the Hammonasset HOF, marsh plants dominated the vegetation, while at the Sherwood HOF, marsh plants were a minor component of a transition zone vegetation dominated by upland grasses. Thus, the rate of foraminiferal migration is unlikely to be identical to that of vegetation migration.

A third important difference between this study and Field et al. (2016b) is the time period analyzed and the inclusion of large storms. There is increasing interest in the role of large storms in driving marsh migration, and more studies of the subject are needed (Fagherazzi et al. 2019). Unlike Field et al. (2016b), our study period happened to include the two highest water levels in the tide-gauge record (Hurricanes Irene and Sandy in 2011 and 2012 respectively). The difference in results between the two studies suggests that it is possible that the majority of the migration that we measured over five decades in fact took place during these two events. If so, the episodic nature of marsh migration may make it challenging to study and to predict. Since our analysis estimated average lateral and vertical migration rates between two discrete time points (1963 and 2016), it cannot resolve any variability in rates within this time period. However, our approach to identifying the leading edge of salt marsh transgression into upland environments is flexible enough to provide additional time points by identifying chronological horizons in the sediment using other dating methods that could, in future work, be used to examine time-variable rates of migration.

Our results (Table 1) suggest that the vertical migration rate over the last 5 decades at Sherwood ( $6.5\text{--}6.6\text{ mm year}^{-1}$ ) was much higher than that at Hammonasset ( $1.7\text{--}2.1\text{ mm year}^{-1}$ ). Those values are, respectively, higher and lower than the rate expected from local RSLR ( $2.9 \pm 0.4\text{ mm year}^{-1}$  measured by the Bridgeport tide gauge over the period 1964–2018; [https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_station.shtml?id=8467150](https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8467150)). The high foraminiferal migration rate at Sherwood is consistent with the fact that foraminifera now occupy unusually high elevations at this site, both in terms of flooding frequency and in relation to vegetation communities.

With only two transects, it is challenging to draw robust conclusions about what drives this difference in migration rate. However, we hypothesize that the difference between sites reflects the differential geographic influence of large storms. In particular, Sandy's storm surge was much higher at Sherwood ( $3.69 \pm 0.03\text{ m}$ ) than at Hammonasset ( $2.20 \pm 0.02\text{ m}$ ; Ostiguy et al. 2018; <https://stn.wim.usgs.gov/fev/#Sandy>), which could potentially help explain the high migration rate at Sherwood. This hypothesis highlights the fact that foraminifera should be considered a *leading indicator* of marsh migration. Given the dominance of upland vegetation at the Sherwood HOF (though with some marsh plants starting to appear), the foraminiferal response to Sandy appears to have been faster than the vegetation response, and it remains to be seen how quickly other aspects of the marsh ecosystem (vegetation, animals, soil biogeochemistry) will follow.

Is it possible that the HOF at Sherwood represents allochthonous foraminifera transported by Sandy's storm surge, rather than true migration? We believe this is unlikely to be a significant factor, given the consistent and widespread

presence of surface foraminifera throughout the transect up to the HOF (Fig. 2), as well as the presence of foraminifera at depths of up to 2.5 cm in core Sherwood A (Fig. 3), which was collected from an elevation only slightly lower than the HOF. Studies of sediment deposited by storm surges or tsunamis indicate that foraminifera tests transported upslope by episodic; high-energy events remain as a stratigraphic anomaly (Pilarczyk et al. 2012; Kosciuch et al. 2018). In contrast, in marshes exposed to a sustained change in tidal flooding regime (through transplantation of a marsh surface or removal of tidal barriers), foraminifera respond rapidly, resulting in a viable population that persists over time and is found in multiple layers of sediment (Engelhart et al. 2013; Horton et al. 2017). We therefore conclude that our evaluation of patterns across multiple, stratigraphically ordered core samples representing multiple years of deposition likely captures a sustained environmental trend—perhaps initiated by a storm event, but persisting beyond it.

Our data demonstrate clearly that both of these LIS marshes—at least as represented by the presence of foraminifera-rich sediment—have in fact moved upslope into upland lawns over the past five decades, although at very different rates. The rapid migration rate at Sherwood is particularly welcome because this marsh has lost significant area to submergence over the same time period (Anisfeld et al. 2016b; Schultz et al. 2016). It remains to be seen how common such rapid migration is in LIS and elsewhere. Our method can be used in future studies of marsh migration into both lawns and forests, including direct comparison with aerial photography analyses.

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