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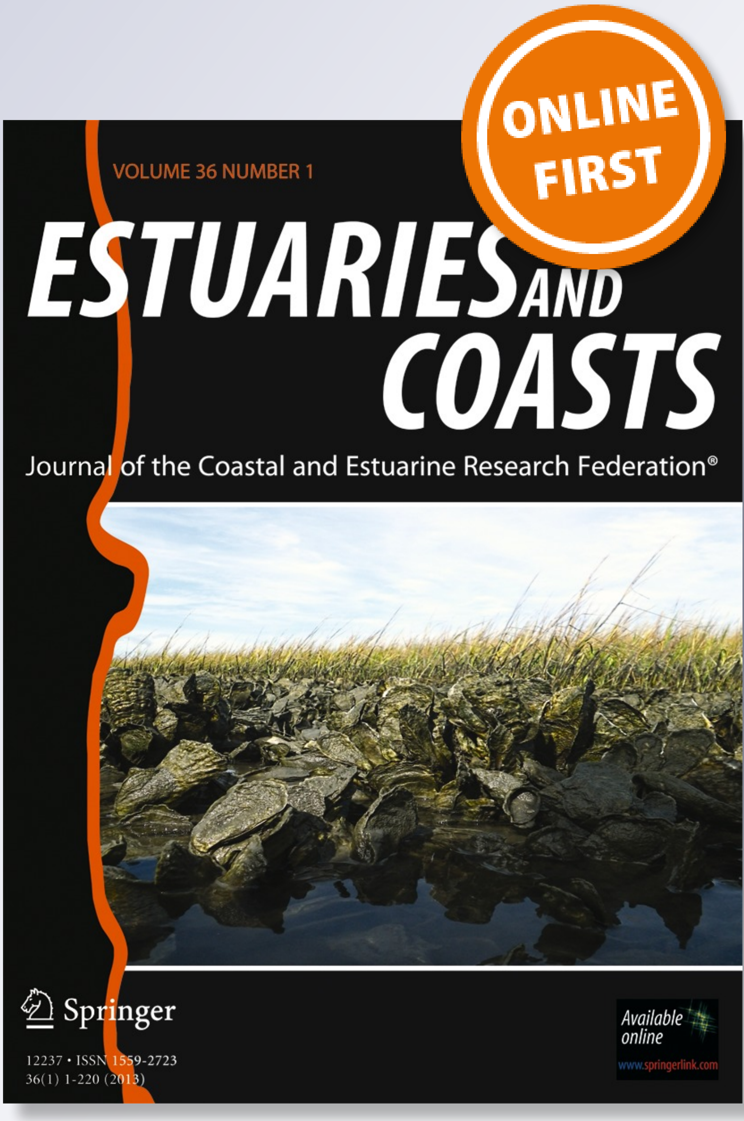

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Sustainability of a Tidal Freshwater Marsh Exposed to a Long-term Hydrologic Barrier and Sea Level Rise

A Short-term and Decadal Analysis of Elevation Change Dynamics

P. Delgado · P. F. Hensel · C. W. Swarth · M. Ceroni · R. Boumans

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Abstract A 115-year-old railroad levee bisecting a tidal freshwater marsh perpendicular to the Patuxent River (Maryland) channel has created a northern, upstream marsh and a southern, downstream marsh. The main purpose of this study was to determine how this levee may affect the ability of the marsh system to gain elevation and to determine the levee's impact on the marsh's long-term sustainability to local relative sea level rise (RSLR). Previously unpublished data from 1989 to 1992 showed that suspended solids and short-term sediment deposition were greater in the south marsh compared to the north marsh; wetland surface elevation change data (1999 to 2009) showed significantly higher elevation gain in the south marsh compared to the north (6±2 vs. 0±2 mm year^{-1}, respectively). However, marsh surface accretion (2007 to 2009) showed no significant differences between north and south marshes (23±8 and 26±7 mm year^{-1}, respectively), and showed that shallow subsidence was an important process in both marshes. A strong seasonal effect was evident for both accretion and elevation change, with significant gains during the growing season and elevation loss during the non-growing season. Sediment transport, deposition and accretion decreased along the intertidal gradient, although no clear patterns in elevation change were recorded. Given the range in local RSLR rates in the Chesapeake Bay (2.9 to 5.8 mm year^{-1}), only the south marsh is keeping pace with sea level at the present time. Although one would expect the north marsh to benefit from high accretion of abundant riverine sediments, these results suggest that long-term elevation gain is a more nuanced process involving more than riverine sediments. Overall, other factors such as infrequent episodic coastal events may be important in allowing the south marsh to keep pace with sea level rise. Finally, caution should be exercised when using data sets spanning only a couple of years to estimate wetland sustainability as they may not be representative of long-term cumulative effects. Two years of data do not seem to be enough to establish long-term elevation change rates at Jug Bay, but instead a decadal time frame is more appropriate.

Keywords Surface elevation change · Accretion · Tidal freshwater marsh · Seasonal sedimentation · Jug Bay · Patuxent River · Sustainability

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Introduction

Riverine flow, storm events, and/or tidal pulses are critical hydrological factors defining the structure and function of

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tidal wetlands (Ward et al. 1998; Day et al. 1999). The pulses of fresh water, sediments, and nutrients create and nourish the highly productive freshwater tidal wetlands (Simpson et al. 1983; Odum et al. 1984). Within a human-dominated landscape, there are numerous ways that these hydrological pulses can be modified and reduced. Built infrastructure such as levees and dams alter natural water flow in and out of the wetlands, often reducing these nourishing pulses (Day et al. 1995; Hensel et al. 1999). Within the Jug Bay tidal freshwater wetlands along the Patuxent River in Maryland, a 115-year-old abandoned railroad levee bisects the wetland complex, perpendicular to the river. As a result, the wetland is split into a northern side (North Glebe Marsh), facing the upper riverine-dominated watershed, and a southern side (South Glebe Marsh), which is more open to the tidal pulses from the Chesapeake Bay.

In addition to experiencing 115 years of altered water flow, this wetland may also be facing the impacts of climate change, particularly those driven by relative local sea level rise (RSLR- eustatic sea level rise plus local land subsidence and dominant coastal currents), including increased flooding and salinity intrusion (Neubauer and Craft 2009). The rate of RSLR in the Chesapeake Bay ranges from 2.9 to 5.8 mm year^{-1} (Boon et al. 2010); in some areas, this is more than twice the rates of published global average estimates (1.5±0.4 mm year^{-1}, Dominguez et al. 2011; 1.59±0.09 mm year^{-1}, Collilieux and Woppelmann 2011) as a result of regional subsidence and changes in coastal currents (Sallenger et al. 2012). Long-term sea level trends at the tide stations nearest to Jug Bay range from 3.2 to 3.4 mm year^{-1} (www.tidesandcurrents.noaa.gov); this appears consistent with the upper range of estimates of regional subsidence (−1.6 to −2.0 mm year^{-1}; Holdahl and Morrison 1974) combined with the global sea level rise rates mentioned above. Projected increases in global sea level rise (e.g., Church and White 2006; Vermeer and Rahmstorf 2009) place future coastal wetland sustainability into question, especially in this region, which has been termed a "hotspot" of accelerated sea level rise (Sallenger et al. 2012). Under the different scenarios of global sea level rise, changes in ocean currents, and local land subsidence, the ability of this particular wetland to gain sufficient elevation is of major importance determining its persistence in the future.

Efforts to create sustainable coastal wetland communities have focused on restoring hydrology. Such activities have ranged from removing fill and recreating tidal channels (Teal and Weishar 2005), to back-filling pipeline canals (Baustian and Turner 2006) and mosquito ditches (Leisnham and Sandoval-Mohapatra 2011; Adamowicz and Roman 2002), and engineering riverine diversions (Lane et al. 2001; Shafroth et al. 2002). At Jug Bay, it is important to understand and evaluate the role of the railroad bed in affecting sedimentation patterns in the large Glebe Marsh system: is the obstruction enhancing or impairing sedimentation and vertical accretion? Determining the long-term accumulated effect of the railroad levee restriction on the marsh sediment dynamics is key to determine its resiliency to climate change, particularly sea level rise.

The ability of coastal wetlands to gain elevation depends on various factors: (1) The availability of sediments, which in tidal freshwater systems is mostly driven by riverine transport from the surrounding watershed (Stoddart et al. 1989). Occasional storm events are expected to facilitate sediment resuspension and sediment delivery to the surface of the wetland by altering flow velocities and flood patterns. (2) The wetland elevation, which affects the frequency and duration of flooding; as a result it is common to see a sediment deposition gradient decreasing from the tidal/riverine channel towards the interior of the wetland (Leonard 1997). (3) Vegetation type and cover as it influences sediment capture and autochthonous soil formation through organic matter production and accumulation (Bricker-Urso et al. 1989; Shi et al. 1995; Leonard and Reed 2002).

Tidal freshwater wetlands are highly diverse systems and although a clear species zonation pattern is not often evident, five major intertidal/supratidal wetland zones are often distinctive: pioneer mudflat, low marsh, mid-high marsh, scrub-shrub, and swamp or riparian forest (Leck et al. 2009). The assemblage of species found within each of these zones is mostly defined by the hydroperiod of each zone, and the resulting vegetation cover plays an important role in determining local patterns of sediment deposition. In salt marshes, for example, *Spartina alterniflora* tends to trap sediments less efficiently than *Spartina patens* due to the lower stem, root and rhizome density of *S. alternifora* (Warren and Niering 1993), whereas taller and denser vegetation, typical of mid-high freshwater marshes, normally retains more sediments (Pasternack and Brush 2001). At Jug Bay, a less dense *Nuphar lutea* community showed higher efficiency capturing sediments than a mixed *Typha* spp.-dominated community, a result of *Nuphar*'s large projected area (a measure taking into account density, volume, and leaf surface area; Cummings and Harris, unpublished data).

This study proposes to determine how a long-term hydrologic alteration (abandoned railroad levee) may affect the ability of a tidal freshwater marsh system to gain elevation as well as to determine its impact on the marsh long-term sustainability to RSLR. Specific questions that will be addressed include: (a) What are the current patterns of marsh sediment availability on either side of the levee? (b) What are the rates of accretion and elevation change in relation to the levee and wetland zones, and how sensitive are these rates to the time period considered? (c) What are the temporal patterns to accretion and elevation change, and how do they relate to riverine discharge? To address these questions, the analysis of short-term measurements of

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accretion, sediment availability and deposition, and long-term measurements of wetland surface elevation were made within the wetland on both sides of the railroad levee and within the low, mid-high, and scrub-shrub wetland zones. Marsh accretion and elevation were measured during the growing season and the non-growing season.

Study Location

The study area is located in the Jug Bay Wetlands Sanctuary, Maryland (38°46′51″N, 76°42′35″W). Jug Bay is a broad, shallow embayment of the upper portion of the tidal Patuxent River, a tributary of the Chesapeake Bay. The Patuxent River, about 171 km long, drains a 2,360-km^2 watershed, and has average flow conditions that range from 7±1 m^3 s^{-1} in the summer to 14±1 m^3 s^{-1} during the spring and winter (USGS gage # 01594440, Bowie, Maryland; Bowie gage). Jug Bay contains extensive tidal freshwater wetlands (489 ha) surrounded mostly by upland forest. Salinity, normally lower than 0.5 ppt, can reach levels of almost 3 ppt under low flow conditions (Baldwin et al. 2001). Although the specific rate of RSLR in Jug Bay is not known, in the Chesapeake Bay it ranges from 2.9 to 5.8 mm year^{-1} (Boon et al. 2010); the nearest long-term National Oceanic and Atmospheric Administration (NOAA) tide gages show a consistent pattern of between 3.2 and 3.4 mm year^{-1} (http://tidesandcurrents.noaa.gov/sltrends).

In 1895, a railroad levee was constructed across a section of the wetland at Jug Bay, bisecting it into what is now known as north Glebe and south Glebe Marsh (referred to henceforth as north and south marsh). Even though this railroad line was abandoned in 1935, the levee has remained. For comparative purposes, the study site includes both sections of this marsh (Fig. 1); within each marsh, sampling stations were located in the low, mid-high, and scrub-shrub zones.

In north and south marshes, the low marsh zone is characterized by highly unconsolidated sediments where *N. lutea* ssp. *advena* (spatterdock) is the dominant species. *Zizania aquatica* (wild rice), *Peltandra virginica* (green arrow arum), *Pontederia cordata* (pickerelweed), and *Sagittaria latifolia* (broadleaf arrowhead) co-occur in this marsh. Except for wild rice and spatterdock, these species often grow in low densities in this low marsh area. The low marsh is flooded for a period of 8–9 h during each semidiurnal tidal cycle to water depths ranging between 30 and 65 cm (Khan and Brush 1994).

Mid- to high marshes at Jug Bay contain the highest diversity of plant species in this system. *Typha* X *glauca*, a hybrid between *T. angustifolia* (narrowleaf cattail) and *T. latifolia* (broadleaf cattail), *Sagittaria latifolia*, *Polygonum arifolium* (halberd-leaved tearthumb), *Impatiens capensis* (jewelweed), *Bidens leavis* (bur marigold), *Leersia oryzoides* (rice cutgrass), and *Phragmites australis* (common reed) are some of the most common species found in this marsh zone. Between the growing and non-growing seasons the appearance in this marsh zone changes significantly as most of the above-ground vegetation senesces with the exception of old culms of *Typha and Phragmites*. The mid-marsh is inundated to an average depth of 20 cm in lower areas and 5 cm in higher areas for a period of 2–4 h during each tidal cycle.

The scrub-shrub wetland occurs at the highest elevations. Species include *Alnus serrulata* (hazel alder), *Acer rubrum* (red maple), *Cornus amomum* (silky dogwood), and *Toxicodendron radicans* (poison ivy). The roots of woody plants form hummocks or small islands within an otherwise lower elevated substrate that is high in decomposed organic matter (muck). The areas between hummocks are flooded for a period of 1–2 h every tide cycle.

Materials and Methods

Different data sets compiled over different time periods were used to characterize sedimentation patterns at the Jug Bay Glebe Marsh. Measurements of total suspended sediments and short-term sediment deposition were made from 1989 to 1992. Marker horizon (accretion) was measured between 2007 and 2009; surface elevation table (SET; elevation change) data spanned from 1999 to 2009, with a 5-year gap between 2002 and 2007.

Marsh Sediment Availability and Short-Term Sediment Deposition

Total suspended solids (TSS) and tide-cycle (short-term) sediment deposition were measured from September 1989 to February 1992, on both sides of the railroad levee and within the three wetland vegetation zones described earlier. Although this sampling took place during an earlier time interval compared to marker horizon and SET measurements, the data provide important insights into sediment delivery to the north and south marshes.

Suspended solids were measured from one-liter samples of surface water collected from the marsh during the flood tide. Approximately 250 ml of each sample was filtered through pre-weighed GFF filters. The filters were dried overnight at 60 °C and weighed to a 0.1-mg precision. A total of 17 sampling events occurred between 1989 and 1992. Differences in TSS among the combinations of marshes and wetland zones were tested using Kruskal–Wallis non-parametric tests (variances were non-homogeneous).

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Short-term sediment deposition was measured at the same time as TSS, using a filter pad technique adapted from Reed (1989). To collect sediment, a 4.7-cm-diameter, pre-weighed GFF filter was attached to a plexiglas plate (25× 40 cm), anchored atop a cinder block set flush to the marsh surface. At each sampling date, at least one filter pad was deployed per study site and marsh zone combination at low tide. Filters were collected at the next low tide (about 6–8 h later). Filters were returned to the laboratory and dried to constant weight at 60°C. A daily sedimentation rate (g m^{-2} day^{-1}) was calculated by dividing the dry weight of sediments accumulated by the fraction of a day that the filters were deployed on the marsh surface. Filters were discarded if they were not submerged, if it rained on them while exposed, or if they were torn. Differences in short-term sedimentation rates among marshes, wetland zones and their interaction were tested with analysis of variance (R version 2.8). Post-hoc multiple comparisons were conducted using a Tukey adjustment.

Spatial and Temporal Patterns of Marsh Surface Elevation and Accretion

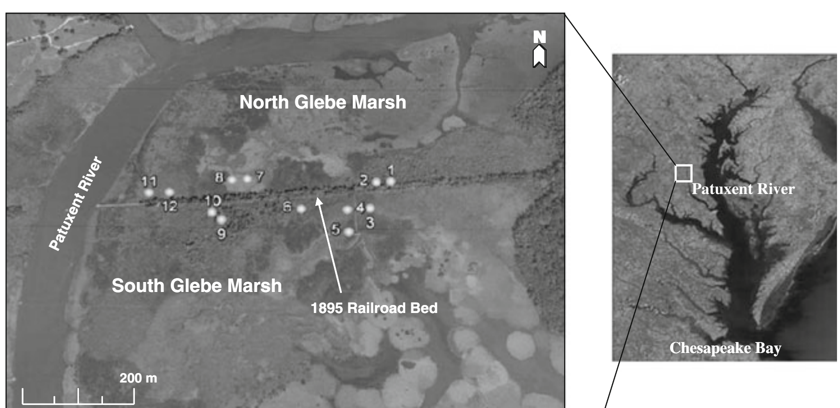
Marsh Surface Elevation (SET Data)

Six first-generation SET stations (Version 2; Cahoon et al. 2002) were established in each of the two marshes (north and south), two replicate stations within each of the three wetland zones (Fig. 1). SET station installation (February 1999) followed typical practices, using a manual post driver (Boumans and Day 1993); insertion depths ranged from 3 to 4 m. SET stations were established at similar distances from tidal channels. During the first 3 years of the study (February1999 to July 2002), each SET station was measured twice a year (late spring or summer and winter or early spring). During the second period of the study (June 2007 – September 2009) SETs were measured at the beginning of each season (late March, late June, late September, and late December). Measurements where the SET pin touched a plant stem, a branch or a large piece of debris were discarded (less than 2 % of records).

Simple linear regressions provided elevation change rates (mm $year^{-1}$) for each of the 36 individual SET pins over the entire 10-year period; the slopes were averaged across the nine pins per position, and across the four positions to the SET station. Analysis of variance (R version 2.8) was used to test for differences among the two marshes, the wetland zones, and their interaction. A logarithmic transformation was used to correct for non-homogeneous variances. Multiple pairwise comparisons were conducted on significant effects using a Tukey adjustment.

Seasonal patterns in elevation change were analyzed by computing incremental elevation change rates at the pin level (in mm $year^{-1}$) over growing (May – September) and non-growing seasons (October – April). Only those time intervals for which one season was clearly defined were included in the analysis. Mixed model analysis of variance (SAS® Proc Mixed, SAS Inc.) was used to test for the significance of the effect of season (growing, non-growing), north vs. south marsh and wetland zone (and their interactions). Model fit was evaluated via Akaike's Information Criterion (AIC). Data were transformed (logarithm) to ameliorate the distribution of residuals.

Daily average Patuxent River discharge at the nearest stream gage station (Bowie gage) was obtained for the second period of the study (2007–2009). The data were summed and averaged for each SET sampling period and correlated to the corresponding incremental elevation change rates.



	North Glebe Marsh	South Glebe Marsh
Scrub-shrub	SET 1-2	SET 9-10
Mid-high marsh	SET 11-12	SET 5-6
Low marsh	SET 7-8	SET 3-4

Fig. 1 Location of surface elevation tables (*SETs*) in the study site at Jug Bay, Patuxent River. Six SETs were established in the north Glebe Marsh and six in the South Glebe Marsh. Photo credit for aerial photo of the Chesapeake Bay: National Oceanic and Atmospheric Administration (NOAA)

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Short and Long-Term Estimates of Marsh Elevation Change (SET Data)

Simple linear regressions were run over an increasing time series, starting with the first measurements (1999) to test for the sensitivity of the results to the particular end point in time. In a similar way, regressions over increasing time intervals were run going backwards in time starting with the last observations in 2009. Regression slopes were averaged to the marsh level (north and south) and compared via *t*-tests. These two approaches provided a better understanding of how the patterns in elevation change rates evolved over time. Ultimately, the 10-year marsh elevation change rates were compared to current estimates of RSLR to determine if the Jug Bay Glebe marsh is keeping pace with sea level rise.

Marsh Accretion (Marker Horizon Data)

Accretion was measured between 2007 and 2009 using feldspar marker horizons. Triplicate feldspar 0.25-m^2 marker horizon plots (Cahoon and Turner 1989) were placed on the wetland soil surface near each SET station during the winter of 2007-2008, and measured at the start of each season at the same time SET measurements were taken. Marker horizon measurements were made following the cryogenic coring technique described by Cahoon et al. (1996). Three cores were collected within each of the three marker horizon plots, and three measurements of accretion above the feldspar layer were taken from each core. Measurements were averaged to obtain a mean value for each marker horizon plot.

Simple linear regressions were estimated for each marker plot, resulting in accretion rate estimates in mm $year^{-1}$; analysis of variance (SAS/STAT® Proc Mixed; SAS Inc. 2008) tested for differences between the two marshes, the three vegetation zones, and their interaction. A logarithmic transformation was used to ameliorate the distribution of residuals. Multiple pairwise comparisons were conducted on significant effects using a Tukey adjustment. Accretion data were also compared to elevation change rates obtained during the same measurement period (2007–2009) to evaluate the magnitude of shallow subsidence in both marshes (Cahoon et al. 1995).

Seasonal analysis followed a similar procedure as for SET data. Accretion was expressed as incremental change per marker plot, over each of the two seasons considered (growing vs. non-growing). Mixed model analysis of variance (SAS® Proc Mixed, SAS Inc.) was used to compare seasons, marsh vegetation zones, and their interactions. A correlation analyses between incremental accretion rates and the Patuxent River discharge was conducted in a similar manner as with the SET data.

Results

Marsh Sediment Availability and Short-Term Sediment Deposition

Total suspended solids (TSS) concentrations decreased over the intertidal gradient, with highest concentrations in the low vegetation zone and lowest concentrations at the scrub-shrub zone (Fig. 2). Significant differences were evident between all three zones ($P \leq 0.03$, Kruskal–Wallis tests). Overall, the south marsh had higher TSS concentrations than the north marsh ($P=0.002$).

Short-term sedimentation was 12±3 and 8±1 g m^{-2} d^{-1} in the south and north marshes, respectively, but the differences were not significant ($P=0.45$). Marsh zone, however, was significant ($P=0.07$), with highest short-term sedimentation in the low vegetation zone (14.2 $gm^{-2}day^{-1}$) and lowest rates in the scrub-shrub zone (5.8 $gm^{-2}day^{-1}$; Fig. 2). The interaction of marshes and zones was not significant ($P=0.68$).

Spatial Patterns of Marsh Elevation and Accretion

The south marsh showed a significantly higher rate of elevation change over the study period (1999 to 2009) compared with the north marsh; average values were 6±2 and 0±2 mm $year^{-1}$, respectively ($P=0.03$). Although there was a trend of higher elevation gain in the mid-marsh (*Typha* spp.) compared to the low and high marsh zones in both marshes, the differences were not significant due to highly variable rates in the south marsh ($P=0.44$). The trends were similar among both marshes, and the marsh–zone interaction was not significant ($P=0.89$).

Accretion rates were not significantly different ($P=0.7$) between the south (26±7 mm $year^{-1}$) and the north marsh (23±8 mm $year^{-1}$). The marsh zone effect, however, was highly significant ($P=0.007$): vertical accretion was significantly higher at the low marsh zone compared with the mid-

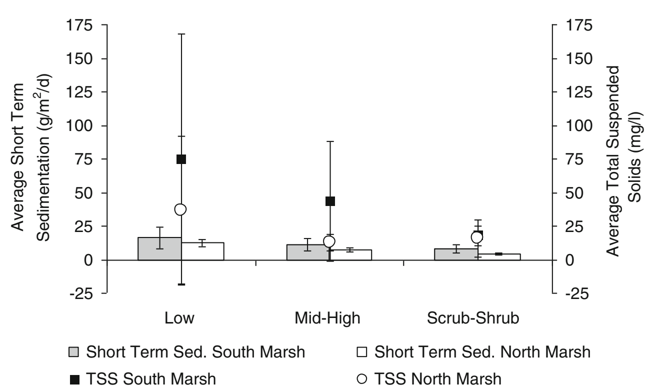

Fig. 2 Total suspended solids (*TSS*) and short-term sedimentation measured at Jug Bay north and south Glebe Marshes and within three intertidal/vegetation zones, Patuxent River

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high and scrub-shrub zones (45±5 vs. 17±5 and 11±5 mm year^{-1}, respectively). The interaction between marshes and zones was not significant (P=0.37).

Over the same interval that accretion measurements were taken (2007–2009), elevation change rates were also similar between the two marshes: 7±1 and 8±2 mm year^{-1} for north and south marshes, respectively. This means that shallow subsidence was roughly similar between the two marshes as well: 16±8 and 18±7 mm year^{-1} for the north and south marshes, respectively (values represent a vertical loss term).

Temporal Patterns of Marsh Elevation and Accretion

There was significantly higher surface elevation gain during the growing season (50±3 mm year^{-1}) than during the non-growing season (−23±3 mm year^{-1}; P<0.0001). In a similar way, vertical accretion rates were significantly higher during the growing season (38±7 mm year^{-1}) than during the non-growing season (12±6. mm year^{-1}; P=0.03). No other effects were significant (P≥0.1).

Daily averaged Patuxent River discharge summed over the measurement intervals explained 88 % and 92 % of the variability in incremental accretion in the north and south marshes, respectively (P≤0.04). There was generally less correlation with elevation change, although daily average discharge, averaged over the measurement intervals, yielded a high correlation with elevation change in the north marsh (87 %; P=0.04).

Short and Long-Term Estimates of Marsh Elevation Change

Relative elevation change (not rates) over the course of the 10-year study showed high variability (Fig. 3). Therefore, calculations of elevation change rates showed similarly high variability over short time periods (especially less than 2 years), with rates ranging from −12 to 58 mm year^{-1} over periods of 6–9 months (Table 1). Regardless of the starting point of the analysis (1999, going forward, or 2009 going backwards in time), significant differences only appeared between north and south marshes after 7 years (Table 1). This result highlights the intrinsic high variability associated with the calculation of elevation change rates when using short-term data compared with long-term data.

Discussion

Long-Term Marsh Sustainability with Respect to RSLR

Elevation gain in the south marsh (6±2 mm year^{-1}) appears sufficient to keep pace with RSLR at present and for the near future. In contrast, the 10-year elevation change rate of the north marsh (0±2 mm year^{-1}) is not sufficient to keep pace with RSLR. This difference in elevation gain between the north and south marshes agrees with an analysis of aerial imagery of this area (Swarth et al., this volume), which shows that between 1971 and 2007 the low marsh-dominant species *N. lutea* has replaced areas previously covered by *Zizania aquatic* in the north marsh (*Z. aquatica* is typically found in slightly higher areas than *N. lutea*). This may be an indication of increased flooding conditions in this area, promoting the colonization of *N. lutea*. The imagery also shows that *N. lutea* is colonizing previously un-vegetated mudflats in the south marsh, possibly a result of sedimentation and vertical accretion. The large difference in elevation change rates between these two adjacent marshes (only separated by an abandoned levee), seems to indicate that the levee plays an important role in shaping the processes that control the elevation change on either side of the levee and probably influences the long-term sustainability of this marsh system to sea level rise.

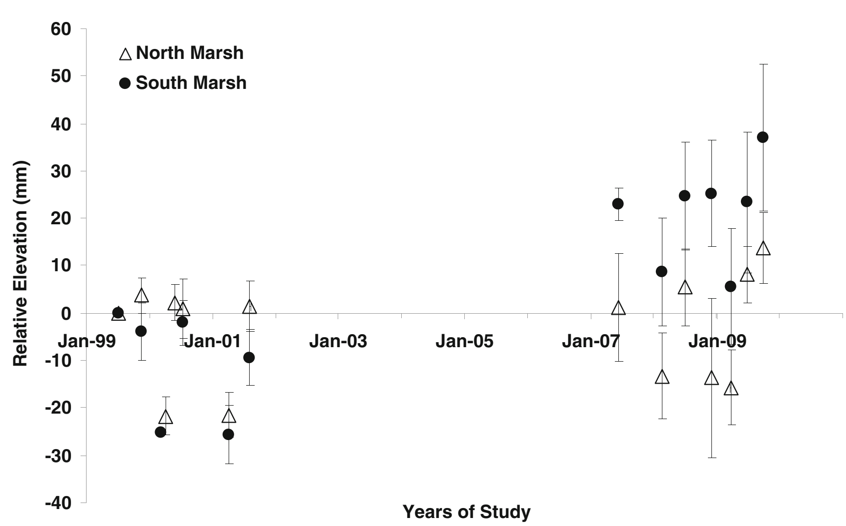

Fig. 3 Elevation change over the course of a 10-year study at the north and south Glebe Marshes in Jug Bay, Patuxent River. The zero point on the ordinate refers to the initial wetland sediment surface observed in 1999, so values on the ordinate are relative to this initial surface

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Table 1 Linear elevation change rates (mm year^{-1}) computed over increasing time intervals over the course of a 10-year study at the north and south Glebe Marshes in Jug Bay, Patuxent River

	Forwards				Backwards			
Date	Years	North Glebe	South Glebe	*P*	Years	North Glebe	South Glebe	*P*
7/8/1999					10.2	−0±1	6±2	*
11/15/1999	0.4	10±16	−12±18		9.9	−0±1	6±2	*
3/8/2000	0.7		−12±18		9.6		6±2	
4/5/2000	0.7	7±17			9.5	0±1		
5/30/2000	0.9	−2±15	8±24		9.3	0±1	6±2	*
7/12/2000	1.0	−3±5	26±18		9.2	1±1	6±2	*
4/4/2001	1.7	−13±3	−6±5		8.5	1±0	7±1	*
8/7/2001	2.1	−5±3	−2±4		8.1	1±1	6±2	*
6/14/2007	7.9	−4±3	1±3		2.3	7±1	8±2	
2/19/2008	8.6	−1±1	5±2	*	1.6	11±3	10±3	
7/3/2008	9.0	−0±1	6±2	*	1.2	9±5	4±5	
12/3/2008	9.4	−1±1	6±2	*	0.8	39±14	17±5	
3/23/2009	9.7	−1±1	5±2	*	0.5	58±6	52±6	
6/25/2009	10.0	−1±1	5±2	*	0.3	29±15	31±6	
9/30/2009	10.2	−0±1	6±2	*				

"Forwards" corresponds to increasing intervals starting in 1999 and going forward; "Backwards" considers intervals from 2009 going back in time

Significant differences ($P<0.05$) between the two wetlands are indicated by the *asterisk* (*) in the *P* column

Little information exists on mechanisms of accretion and elevation change in riverine, tidal freshwater systems. Generally, the river is seen as an important source of sediments (Childers et al. 1993; Pasternack and Brush 1998). In many coastal settings episodic pulsing events such as storms, hurricanes, and riverine flooding have also showed to be important in sediment delivery to wetlands (Hensel et al. 1998; Day et al. 2002; Cahoon 2006). At Jug Bay, the TSS and short term sedimentation data support the notion that sediments are available for deposition (Fig. 2). In addition, accretion data showed a positive correlation with river discharge. However, riverine sedimentation alone is not providing enough elevation gain in the north marsh to keep pace with the rising sea levels. Although accretion was similar between the two marshes over the 2007–2009 study period, the 10-year elevation trends show the south marsh gaining elevation at a much faster rate than the north. High spatial variability in elevation trajectories was seen along the Patuxent River (Childers et al. 1993), and may be related to a number of factors causing one location to act as a more efficient sediment trap. At Jug Bay, the long-term presence of the levee may be impacting a variety of sedimentation drivers such as tidal and riverine fluxes, wind driven resuspension, and water residence time, which may have led to differences in the elevation trajectories between both sides of the levee.

Deposition does not always lead to elevation gain. At Jug Bay, a high riverine discharge event occurred during the sedimentation study (May 2008; 170 m^{3}s^{-1}; Bowie gage). This event may have led to the highest accretion interval recorded: 31±5 and 40±16 mm year^{-1} for north and south marshes, respectively. Despite this one event, the accompanying elevation change was very low: 0±2 and 2±0 mm year^{-1} for the north and south marshes, respectively. The lack of correspondence between accretion and wetland elevation change is well documented (Cahoon et al. 1995; Hensel et al. 1999; Reed 2002; Cahoon 2006). The Jug Bay Glebe Marsh likewise shows high rates of shallow subsidence (16–18 mm year^{-1}, south and north, respectively). Compaction, de-watering, and decomposition of organic matter can lead to localized shallow subsidence. Jug Bay marshes could certainly lose elevation due to decomposition; however, even a small amount of soil organic matter is important for vertical growth (Nyman et al. 2006; Neubauer 2008). Although differences in shallow subsidence may explain part of the differences between the net elevation trajectories of north and south marshes, the contribution of below-ground production (not available in this study) could also influence the observed patterns.

Spatial and Temporal Patterns of Marsh Elevation Change and Accretion

Vertical accretion showed positive gains in three of the four intervals within the 2007–2009 study period, indicating that erosion is not a dominant process determining local spatial sedimentation patterns within this marsh. The one interval where erosion was recorded was over the winter (−9±4 mm year^{-1}), in the north marsh's low zone (−22±3 mm year^{-1}). At the Otter Point Creek tidal freshwater marsh in the Bush River, Maryland, four of

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30 sites measured showed erosion; two in each of the low and the high marshes. Most of the erosion occurred during winter (Pasternack and Brush 2001). Vertical accretion showed a spatial pattern with higher sediment deposition in the low marsh, which progressively decreased going up the intertidal gradient. This result confirms the pattern seen in TSS, indicating greater sediment availability at lower intertidal zones. This follows well-established patterns reported for other wetlands (Stoddart et al. 1989; Pasternack and Brush 1998; Neubauer et al. 2002; Darke and Megonigal 2003). Higher sediment accumulation on the lower marsh is probably driven by higher duration and frequency of flooding compared with the marsh interior (Cahoon et al. 1995).

Accretion and elevation change showed very strong seasonal dynamics, similar to those described by Orson et al. (1992), Pasternack and Brush (1998, 2001), and Darke and Megonigal (2003). Accretion was over three times greater in the growing season (spring and summer) compared to the non-growing season (fall and winter). During the non-growing season, the Jug Bay Glebe Marsh experienced elevation loss (on ten different measurements by more than 100 mm year^{-1}) followed by elevation gain during the growing season. During the non-growing season the marsh surface becomes more exposed due to the loss of vegetation and the physical action of the tides, winds, and storms. Ice formation and melting, and other weather-related events may also contribute to the loss or re-distribution of materials from the marsh surface. In contrast, during the growing cycle, vegetation growth contributes to sediment retention, and the biomass and sediments deposited from the previous year contribute to elevation gain and soil formation (Pasternack and Brush 1998). Seasonal variations in elevation change had been documented previously in Jug Bay (Childers et al. 1993), although the short 2.5-year data set did not show consistent trends. The authors found, however, that river discharge was a significant predictor of elevation gain at two of the seven stations.

In this study, accretion correlated best with the sum of all riverine flows. However, the resulting elevation change, which includes shallow subsidence, is more related to average river flow during a measurement interval, deemphasizing the impact of episodic river flow events. Pulsing events are not solely restricted to riverine flow; coastal storms can also mobilize sediments on wetland surfaces (Cahoon 2006). For example, the Mataponi Creek marsh, which is 5 km downstream from the study area, experienced about 23 mm of sediment deposition after Hurricane Irene and Tropical Storm Lee in September 2011 (Delgado, unpublished data). This study also showed that caution should be exercised in making broad statements when averaging over temporally variable data. For example, the short-term sedimentation data showed an average sediment deposition of 12 gm^2 day^{-1} for the south marsh and 8 gm^2 day^{-1} for the north marsh. The observed difference between these values was entirely due to one large episodic event which caused up to 100 gm^{-2}day^{-1} on filter pads in the south marsh (July 1991) —— one order of magnitude higher than 76 % of the data. The impact of this event extended into the subsequent sampling (September 1991), when sedimentation remained high (50–90 gm^{-2}day^{-1}). Outside this event, the south actually saw less sedimentation on filter pads than the north (average 4.6 gm^{-2}day^{-1}, compared to 7.8 gm^{-2}day^{-1}).

The Importance of Time Scales of Measurements

It is important to realize that the differences in accretion and elevation trends may also be related to the different time periods over which measurements are taken. For example, when we restrict the analysis to the second study period (2007–2009), we found that elevation change was essentially the same for the north (7±1 mm year^{-1}) and south marsh (8±2 mm year^{-1}). This means that accretion and shallow subsidence acted similarly in affecting elevation change in both marshes. In other words, the significant differences in the 10-year elevation change trajectories relied exclusively on the elevations at the beginning and the end of the 10-year period (Fig. 3). Neither end point seems more important than the other: regardless of where in time one is computing rates, there appears to be high short-term variability. Two years of data do not seem enough to establish long-term elevation change rates at Jug Bay. These results suggest that short-term rates are more sensitive to specific sedimentation or erosion events and as the time period grows the importance of these pulsing events are better integrated in the long-term trend. At Sweet Hall Marsh in Virginia, Neubauer et al. (2002) showed a decrease in accretion rate with increasing time scale (from weeks to months, decades, and centuries), which was attributed to mineralization of recently deposited sediments, erosion from storm events, and historical variability in sediment deposition rates. To assess wetland sustainability, however, one needs to consider both the time scale over which important ecosystem drivers exist (Day et al. 1995) but also those drivers to which the wetland community adapts. The decadal time frame would be a reasonable approach within Jug Bay and for others studying freshwater tidal wetlands elsewhere.

Conclusions

Sea level change impacts will occur within a human-dominated landscape where anthropogenic and environmental stressors are already present. For over a century, the Jug Bay Glebe Marsh has experienced the effects of the hydrological restriction caused by the presence of the railroad levee. This study has shown that the south marsh

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(downstream of the levee) which is open to unrestricted tidal fluxes appears to be sustainable with respect to current rates of RSLR, while the long-term sustainability of the north marsh (upstream of the levee) appears to be in jeopardy. An important conclusion of this study is that the lack of elevation gain in the north marsh occurs despite the availability of riverine sediments, which appears to be comparable to the south marsh. In addition, both sides of the levee showed similar high rates of shallow subsidence. The results of this study suggest that other factors such as infrequent episodic events may play an important role in allowing the south marsh to keep pace with sea level rise; however, more data are needed to better understand these processes. This study, therefore, shows the importance of long-term data records to estimate rates and to understand the processes of wetland elevation change. Caution should be exercised when using short-term data sets to estimate rates of marsh surface elevation change, as they may not be representative of long-term cumulative effects. Additionally, data collection for short and long-term studies could be improved by augmenting the number of replicate SET stations utilized for hypothesis testing.

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