

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science



journal homepage: www.elsevier.com/locate/ecss

Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation

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ARTICLE INFO

Article history: Received 5 December 2008 Accepted 30 January 2009 Available online 11 February 2009

Keywords: salt marsh organic sediments accretion sea-level rise belowground biomass carbon storage

ABSTRACT

Salt marshes accrete both organic and inorganic sediments. Here we present analytical and numerical models of salt marsh sedimentation that, in addition to capturing inorganic processes, explicitly account for above- and belowground organic processes including root growth and decay of organic carbon. The analytical model is used to examine the bias introduced by organic processes into proxy records of sedimentation, namely ¹³⁷Cs and ²¹⁰Pb. We find that accretion rates estimated using ²¹⁰Pb will be less than accretion rates estimated using the ¹³⁷Cs peak in steadily accreting marshes if (1) carbon decay is significant and (2) data for ²¹⁰Pb extend below the ¹³⁷Cs peak. The numerical model expands upon the analytical model by including belowground processes such as compaction and root growth, and by explicitly tracking the evolution of aboveground biomass and its effect on sedimentation rates. Using the numerical model we explore how marsh stratigraphy responds to sediment supply and the rate of sealevel rise. It is calibrated and tested using an extensive data set of both marsh stratigraphy and measurements of vegetation dynamics in a Spartina alterniflora marsh in South Carolina, USA. We find that carbon accumulation in marshes is nonlinearly related to both the supply of inorganic sediment and the rate of sea-level rise; carbon accumulation increases with sea-level rise until sea-level rise reaches a critical rate that drowns the marsh vegetation and halts carbon accumulation. The model predicts that changes in carbon storage resulting from changing sediment supply or sea-level rise are strongly dependent on the background sediment supply: if inorganic sediment supply is reduced in an already sediment poor marsh the storage of organic carbon will increase to a far greater extent than in a sediment-rich marsh, provided that the rate of sea-level rise does not exceed a threshold. These results imply that altering sediment supply to estuaries (e.g., by damming upstream rivers or altering littoral sediment transport) could lead to significant changes in the carbon budgets of coastal salt marshes.

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1. Introduction

Salt marsh ecosystems play a vital role in the dissipation of wave energy, accretion of sediment, filtration of nutrients, and as habitats for commercially important fisheries. Global eustatic sea-level over the past 100 years is estimated to have risen at a rate of $1-2 \text{ mm yr}^{-1}$, yet rates over the period of 1993–2002 are greater than the global average (Holgate and Woodworth, 2004). Early studies of salt marsh accretion recognized positive feedbacks between inorganic sedimentation and marsh accretion (e.g., Krone, 1987; French, 1993; Allen, 1995). For example, increasing the rate of sea-level rise will increase the duration of inundation on the marsh, thus increasing sedimentation due to settling of inorganic sediment. In contrast, reduced rates of sea-level rise will result in decreased inundation and decreased sedimentation. It has been long recognized that many marshes are able to keep pace with sealevel rise (Friedrichs and Perry, 2001), and that ability depends on the complex interplay between marsh hydrodynamics, vegetation, and sedimentation. In addition, many authors have found that marsh vegetation is most productive at an optimum elevation relative to sea level (e.g., Redfield, 1972; Orson et al., 1985). Morris et al. (2002) used intensive measurements of biomass to quantify this optimum range for Spartina alterniflora. By coupling these data to a model of marsh sedimentation, Morris et al. (2002) found that current rates of sea-level rise in South Carolina, USA will eventually result in the drowning of local Spartina marshes. This finding underlines the need to better understand the relationship between vegetation, sedimentation, and sea-level rise.

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^{0272-7714/\$ –} see front matter \odot 2009 Elsevier Ltd. All rights reserved. doi:10.1016/j.ecss.2009.01.028

A number of modelling studies have incorporated the feedbacks between vegetation, sedimentation and sea-level rise (e.g., Mudd et al., 2004; D'Alpaos et al., 2007; Kirwan and Murray, 2007), but these models have yet to incorporate sediment compaction and belowground biomass production. It is becoming clear, however, that belowground biomass production plays a key role in maintaining marsh surface elevations (e.g., Nyman et al., 2006; Mckee et al., 2007: Neubauer, 2008). In addition, while inorganic sediments are relatively incompressible over time, this is not the case for organic sediment: in some marshes the volume of void spaces and water associated with organic material is 90% (Turner et al., 2001). Early diagenetic models (e.g., Westrich and Berner, 1984) addressed decomposition of organic sediments but lacked descriptions of other processes such as root growth and compaction. The next generation of models quantified different suites of belowground processes (Morris and Bowden, 1986; Rybczyk et al., 1998; Day et al., 1999; Rybczyk and Cahoon, 2002), but these models have not included the explicit feedbacks between sedimentation, sea level, and biomass dynamics first reported by Morris et al. (2002).

In addition to influencing marsh accretion rates, organic sedimentation allows marshes to serve as carbon sinks (e.g., Chmura et al., 2003). The peraquaic moisture regime and prevalence of anaerobic decomposers in coastal marsh ecosystems reduce the efficiency of organic matter decomposition and promote the sequestration carbon (Hussein et al., 2004). Finally, carbon decay can influence the interpretation of two radioisotopes commonly used in dating of marsh sediments: ²¹⁰Pb and ¹³⁷Cs (Appleby and Oldfield, 1992). Turner et al. (2006) observed differences between accretion rates from ²¹⁰Pb and ¹³⁷Cs and hypothesized that these differences could be the result of organic matter compaction or decomposition. Despite the importance of organic decomposition in making estimates of accretion rates using ²¹⁰Pb and ¹³⁷Cs, which are frequently used to estimate marsh accretion on decadal scales, there has been no study that combines an explicit representation of belowground processes such as organic decay and root growth, and their dependence on aboveground processes, with radioisotope deposition. This study addresses this important issue.

Here we present two models to understand both the influence of organic deposition on the interpretation of dating methods and also to examine the relative balance and feedbacks between organic vs. inorganic sedimentation on coastal salt marshes. These two models are the first to couple the feedback between biomass production, sedimentation and sea-level rise first outlined by Morris et al. (2002) with an explicit representation of belowground processes. The resulting models allow us to predict sediment characteristics as a function of depth on a salt marsh. We have specifically designed the models to predict characteristics that are likely to be measured in the field, e.g., carbon content, porosity, and the concentration of radioisotopes. The first model is a simplified analytic model that captures some essential features of marsh sedimentation. The second model is a numerical model that can account for sediment compaction, depth-dependent root growth, feedbacks between biomass and sedimentation, and belowground decay of organic carbon. This numerical model, which is tested using data from a well-studied site in the Atlantic coast of the United States, is used to examine fundamental relationships between carbon accumulation and storage as they are affected by changes in sea-level rise and changing sediment supplies. We call these models OIMAS-A and OIMAS-N (Organic-Inorganic Marsh Accretion and Stratigraphy-Analytical and Numerical, respectively).

2. OIMAS-A: a simplified analytical model

In this section we construct a mathematical model (OIMAS-A) that is highly simplified yet can be used to illustrate some of the

essential features of the competition between organic and inorganic sedimentation on salt marshes. Organic sediment consists of refractory (it does not decay) and labile (it does decay) fractions. In the OIMAS-A model we consider a situation in which the decay rate of labile organic matter does not depend on its depth below the marsh surface. Although labile carbon is present near the surface, and contributes to the carbon storage in the marsh sediment, it does not contribute to marsh accretion or carbon sequestration because any labile carbon deposited decays from the system after a given amount of time (by definition).

Numerous authors have documented a series of feedbacks that allow salt marshes under a range of conditions to keep pace with sea-level rise (e.g., Pethick, 1981; Krone, 1987; Chmura et al., 1992; French, 1993; Allen, 1995; Morris et al., 2002). Here we consider a point on the marsh surface that is in an equilibrium situation in which the rate of sea-level rise (*RSLR*, dimensions LT^{-1} , dimensions henceforth reported in [M]ass, [L]ength and [T]ime in square brackets) is matched by marsh accretion:

$$RSLR = \frac{1}{\varphi} \left(\frac{R_{\text{ref}}}{\rho_{\text{o}}} + \frac{R_{\text{s}}}{\rho_{\text{s}}} \right)$$
(1)

where φ [dimensionless] is the porosity of the marsh sediment at a depth below which porosity does not change, ρ_0 [M L⁻³] is the density of organic material, ρ_s [M L⁻³] is the density of the inorganic material, R_{ref} [M T⁻¹ L⁻²] is the mass supply rate per unit area of refractory organic matter, and R_s [M T⁻¹ L⁻²] is the mass supply rate per unit area of inorganic sediment. These mass supply rates are net supply rates (i.e. deposition minus erosion).

2.1. Accumulation and storage of organic and inorganic mass

Simple rearrangement of Eq. (1) shows that in the equilibrium situation any decrease in the supply of inorganic sediment must be compensated by an increase in refractory organic matter:

$$R_{\rm ref} = \rho_0 \varphi RSLR - R_s \frac{\rho_0}{\rho_s}.$$
 (2)

In general, organic matter is thought to exist in a number of pools (e.g., Baisden and Amundson, 2003; Jenkinson and Coleman, 2008) with different decay rates; we account for a 'fast' and 'slow' and refractory pool of organic matter in the OIMAS-A model. The total mass supply rate per unit area at which organic material is added to the marsh ($R_{\rm org}$) is:

$$R_{\rm org} = R_{\rm ref} + R_{\rm lsl} + R_{\rm lfa}, \tag{3}$$

where the subscripts lsl and lfa represent slow labile and fast labile pools, respectively. Suppose that the relative proportions of refractory and labile organic matter in organic sediment are constant such that:

$$R_{\rm lsl} = R_{\rm org} \chi_{\rm lsl}, \tag{4a}$$

$$R_{\rm lfa} = R_{\rm org} \chi_{\rm lfa}, \tag{4b}$$

and

$$R_{\rm ref} = R_{\rm org} \left(1 - \chi_{\rm lsl} - \chi_{\rm lfa} \right) = R_{\rm org} \chi_{\rm ref}, \qquad (4c)$$

where $\chi_{\rm Isl}$ [dimensionless] is the fraction of deposited organic matter that goes into the slow labile pool, $\chi_{\rm Ifa}$ [dimensionless] is the fraction of deposited organic matter that goes into the fast labile pool, and $\chi_{\rm ref}$ [dimensionless] is the fraction of deposited organic matter that goes into the refractory pool. The total supply of mass to

the marsh surface per unit area, R_{tot} [M T⁻¹ L⁻²], is $R_s + R_{org}$. When marsh accretion keeps pace with sea-level rise, this is equal to:

$$R_{\text{tot}} = R_{\text{s}} + \frac{R_{\text{ref}}}{\chi_{\text{ref}}} = R_{\text{s}} + \frac{1}{\chi_{\text{ref}}} \left(\rho_{\text{o}} \varphi RSLR - R_{\text{s}} \frac{\rho_{\text{o}}}{\rho_{\text{s}}} \right).$$
(5)

Although the labile fractions do not contribute to carbon sequestration (due to decay), there is some finite amount of labile organic matter stored in the marsh column. The mass of labile organic matter above a layer deposited at time *T* before present is:

$$M_{\rm lsl} = \int_{0}^{T} R_{\rm lsl} e^{-k_{\rm lsl}t} \, \mathrm{d}t = \frac{\chi_{\rm lsl} R_{\rm ref}}{\chi_{\rm ref} k_{\rm lsl}} \Big(1 - e^{-k_{\rm lsl}T}\Big), \tag{6}$$

where $k_{\rm lsl}$ [dimension T⁻¹] is the decay coefficient of the slow labile organic matter. We omit the equation for fast labile organic matter because it takes the same form as Eq. (6). As *T* becomes large (e.g., $T \gg 1/k_{\rm lsl}$), the exponential term in Eq. (6) goes to zero and we find that the labile organic matter stored in the marsh column is linearly proportional to the rate of mass accumulation of refractory organic material. We can similarly find the total sediment above a layer deposited at time *T*:

$$M_{\text{tot}} = \int_{0}^{T} R_{\text{s}} + R_{\text{ref}} + R_{\text{lfa}} e^{-k_{\text{lfa}}t} + R_{\text{lsl}} e^{-k_{\text{lsl}}t} dt$$

= $R_{\text{s}}T + \left(RSLR - \frac{R_{\text{s}}}{\rho_{\text{s}}\varphi}\right) \left[T + \frac{\chi_{\text{lfa}}}{\chi_{\text{ref}}k_{\text{lfa}}} (1 - e^{-k_{\text{lfa}}T}) + \frac{\chi_{\text{lsl}}}{\chi_{\text{ref}}k_{\text{lsl}}} (1 - e^{-k_{\text{lsl}}T})\right].$ (7)

Eq. (7) may be used in conjunction with the density and porosity of the respective sediments to find the depth, d [dimensions L], of a layer of age *T*:

$$d = \frac{R_{\rm s}T}{\rho_{\rm s}\varphi} + \left(RSLR - \frac{R_{\rm s}}{\rho_{\rm s}\varphi}\right) \left(T + \frac{\chi_{\rm lsl}\left[1 - e^{-k_{\rm lsl}T}\right]}{k_{\rm lsl}\chi_{\rm ref}} + \frac{\chi_{\rm lfa}\left[1 - e^{-k_{\rm fal}T}\right]}{k_{\rm lfa}\chi_{\rm ref}}\right).$$

$$(8)$$

If there is no decomposition of carbon and the marsh is steadily accreting, the relationship between depth and age is linear. This relationship is more complex in near-surface sediments where labile material is still present; the presence of this labile material may convolute the interpretation of marsh accretion rates using fallout radioisotopes, as we shall demonstrate below.

2.2. Interpretation of accretion rates

The use of ²¹⁰Pb and ¹³⁷Cs has become widespread in the analysis of marsh sedimentation, and we can use the OIMAS-A model to illustrate the biases of these methods under the idealized conditions of the model. If the radioisotopes ²¹⁰Pb and ¹³⁷Cs are used to determine accretion rates, a number of factors can lead to uncertainty in the results. The OIMAS-A model can illustrate the effects of two of these factors, namely the enrichment of the radioisotopes due to loss of organic matter and the nonlinear relationship between depth in the marsh column and age of the sediments at a given depth, also caused by organic decay. We neglect the effects of autocompaction; this added complexity is later introduced into the OIMAS-N model.

Two scenarios are often considered for the deposition of ²¹⁰Pb (e.g., Appleby and Oldfield, 1992): the constant initial concentration (CIC) scenario (wherein sediment being deposited on the surface of

the marsh contains a constant concentration of ²¹⁰Pb) and the constant rate of supply (CRS) scenario (wherein ²¹⁰Pb is deposited at some fixed rate such that its concentration in surface sediments is inversely proportional to the accretion rate). For the simple steady-state accretion scenarios investigated in this section, these two scenarios of ²¹⁰Pb deposition yield the same results.

The concentration of lead that remains in the marsh column after some time *T* is enriched due to the decay of organic sediment. Following Appleby and Oldfield (1992), we define an enrichment factor, η , that can be determined for a given time after deposition as

$$\eta = \frac{RSLR\varphi\rho_{o}\rho_{s} - R_{s}(\rho_{o} - \rho_{s}\chi_{ref})}{R_{s}\rho_{s}\chi_{ref} + \rho_{o}(\rho_{s}\varphi RSLR - R_{s})(\chi_{ref} + \chi_{lsl} e^{-k_{lsl}T} + \chi_{lfa} e^{-k_{fal}T})}$$
(9)

For a given supply of ²¹⁰Pb, one can calculate the age of a sediment using the relationship $T_{app} = -\ln(C/C_0)/\kappa$, where κ [dimensions T⁻¹] is the ²¹⁰Pb decay constant. This age, however, is an apparent age because it does not account for enrichment of the sediment due to organic decay. The ratio of the true age of a sediment layer and the apparent age is:

$$\frac{T_{\text{app}}}{T} = 1 - \frac{\ln(\eta)}{T_{\kappa}}.$$
(10)

Thus, a layer dated by comparing its excess ²¹⁰Pb content with the excess ²¹⁰Pb concentration of surface layer will be older than its apparent age.

In contrast to ²¹⁰Pb, dating of layers using ¹³⁷Cs is performed by identifying a peak in the ¹³⁷Cs concentration. It is typically assumed that the peak ¹³⁷Cs concentration represents approximately the year 1963, so the apparent accretion rate would be the depth of the layer deposited in 1963 divided by the time since the year 1963. If the age of the layer were calculated using ²¹⁰Pb, the apparent age would be less than the true age so the apparent accretion rate as measured by ²¹⁰Pb will always be greater than the accretion rate measured by ¹³⁷Cs. This is the opposite of the trend found by Turner et al. (2006), who compiled a large number of studies that estimated marsh accretion using ²¹⁰Pb and ¹³⁷Cs. Accretion rates determined by ²¹⁰Pb, are not, however, typically calculated by dividing the depth of a layer by its apparent time of deposition; rather ²¹⁰Pb accretion rates are generally determined by the slope of the relationship between the logarithm of the ²¹⁰Pb activity and depth (e.g., Lynch et al., 1989; Orson et al., 1998; Anisfeld et al., 1999; Donnelly and Bertness, 2001; Turner et al., 2006). Thus, organic decay affects the accretion rate as estimated by ²¹⁰Pb not only by enriching the concentration of ²¹⁰Pb in a given layer, as described by Appleby and Oldfield (1992), but also by influencing a layer's depth below the surface as a function of its age (i.e., Eq. (8)).

The decay of carbon, through both of the above mechanisms, leads to overestimation of the accretion rate when using ²¹⁰Pb and ¹³⁷Cs. Because the rate of carbon loss is greatest near the surface, the overestimation of accretion rates using the two radioisotopes is most severe near the surface. We demonstrate the effect of decomposition by plotting the logarithm of ²¹⁰Pb concentration in an idealized core that contains labile carbon (Fig. 1). The accretion rate on the marshes shown in Fig. 1 is 2.5 mm yr⁻¹, whereas the accretion rates estimated from the predicted profiles (each representing 150 years of deposition) range from 2.53 mm yr⁻¹ (for $R_{\rm s} = 2.0$ kg m⁻² yr⁻¹, $\chi_{\rm ref} = 0.4$, and $\chi_{\rm lsl} = 0.1$) to 6.16 mm yr⁻¹ (for $R_{\rm s} = 1.0$ kg m⁻² yr⁻¹, $\chi_{\rm ref} = 0.1$, and $\chi_{\rm lsl} = 0.5$). In extreme cases the concentration of ²¹⁰Pb will increase with depth near the surface, this is because the decay of organic carbon outpaces the decay of ²¹⁰Pb near the surface of the marsh. Deeper in the column the decrease in ²¹⁰Pb activity with depth better represents the true accretion rate because much of the labile carbon has been removed via decay.



Fig. 1. Activity plots of 210 Pb in a marsh accreting at 2.5 mm yr⁻¹ for different rates of inorganic sediment supply and different proportions of deposited labile carbon. The decay constant for the fast labile pool is 0.2 yr⁻¹, based on the measurements of Conn and Day (1997). The slow labile pool is set an order of magnitude slower than the fast labile pool for simplicity. Parameter values not shown on plot are selected to be typical of marsh sediments: $\varphi = 0.4$, $\rho_o = 1200 \text{ kg/m}^3$, $\rho_s = 2200 \text{ kg/m}^3$.

An important implication of the effect of organic decay on radio isotope decay profiles is that if the marsh core sampled for ²¹⁰Pb data extend below the ¹³⁷Cs peak, then the accretion rate estimated by ¹³⁷Cs will be greater than that estimated using ²¹⁰Pb (Fig. 2). This is the case for nearly all of the cores compiled by ^{Turner} et al. (2006). The reason for this bias in most cases is that ²¹⁰Pb can be measured in sediments up to \sim 150 years in age (e.g., Appleby and Oldfield, 1992), whereas the ¹³⁷Cs peak is much younger and the sediment above the peak has yet to fully undergo organic matter decomposition and attendant loss of volume near the surface. These results do not necessarily mean that the trends in the data compiled by Turner et al. (2006) are due solely to decomposition; the studies cited by Turner et al. (2006) were in marshes that may not adhere to the strict assumptions of the OIMAS-A model. Nonetheless, the results presented here show that a discrepancy in accretion rates determined by the two radioisotopes do not necessarily indicate a change in accretion rate; indeed such discrepancies can occur in steadily accreting marshes. Interestingly the ratio between accretion rates estimated by the two isotopes predicted by the OIMAS-A model is independent of the rate of sealevel rise. Instead the ratio in apparent accretion rates is most sensitive to both the percent of refractory carbon and the relative proportions of labile carbon in the depositing sediment (Fig. 2). Fig. 2 shows that ²¹⁰Pb and ¹³⁷Cs can be used with confidence in marshes whose sediments are made primarily of inorganic sediment, but if transient marsh accretion is to be confirmed or refuted in organic rich environments it is quite important to quantify the decomposition regime of the marsh.

3. OIMAS-N: the numerical model

Although the OIMAS-A model can yield insights into the basic feedbacks between organic and inorganic sedimentation, and the

effects of decomposition on the estimation of marsh accretion rates, it contains by necessity restrictive assumptions. Relaxing these assumptions precludes analytical solution of the governing equations, and we have therefore constructed a more flexible numerical model that can account for a rich array of evolving salt marshes called OIMAS-N.

The OIMAS-N model simulates the transient evolution of a sediment column situated within a salt marsh. Similar to the OIMAS-A model, this column of sediment may accrete through both organic and inorganic sedimentation. Unlike the OIMAS-A model, the numerical model includes the additional processes of depth-dependent root growth, plant growth and mortality, and sediment compaction. In addition, the OIMAS-N is fully transient. Organic material is added to the column through growth of belowground biomass and the deposition of litter on the column's surface, and is lost due to decomposition. Inorganic material is added due to particles settling from tidally induced floods, and trapping of particles by salt marsh macrophytes; this sediment is deposited at the surface of the column. Erosion by storms can also be simulated by removing material from the surface of the column. The elevation of the surface changes due to erosion, sedimentation, and compaction, and OIMAS-N tracks the composition of the marsh sediments as a function of depth below the surface.

3.1. Organic component

Live macrophytes on salt marshes produce biomass. This biomass may be deposited both above and below the marsh surface. This material can be lost due to either erosion or decomposition. The amount of organic material that is added to the column at any time is a function of the biomass present on the marsh surface (e.g., Morris et al., 2002; Nyman et al., 2006).



Fig. 2. The ratio between the accretion rate estimated by ²¹⁰Pb (Sed₂₁₀) and by ¹³⁷Cs (Sed₁₃₇) as a function of the fraction of the deep sediments that are refractory carbon (i.e., $f_{ref} = R_{ref}/(R_{ref} + R_s)$). The ¹³⁷Cs peak is 45 years old in these columns, and ²¹⁰Pb accretion rate is estimated by regression of the ²¹⁰Pb activities using sediment representing 50 and 150 years of sedimentation. Parameter values are the same as in Fig. 1 unless noted in the plot. The grey region demarcates where Sed₂₁₀/Sed₁₃₇ < 1.

3.1.1. Growth of macrophytes

A number of studies have investigated the relationship between the biomass and the edaphic factors controlling biomass of salt marsh macrophytes. For example, Valiela et al. (1978) found that fertilization could induce short form Spartina alterniflora to grow to resemble the tall form, and hypothesized that increased nutrient availability near marsh creeks could induce greater biomass on marsh platforms. King et al. (1982) found that increased sulfide concentrations in marsh interstitial water could inhibit macrophyte growth, and attributed spatial variations in biomass to the flushing frequency of marsh sediment. Both nutrient supply and flushing of sulfides are related to the inundation frequency of a given location on a salt marsh. Using biomass measurements collected on a natural salt marsh, Morris et al. (2002) found that biomass of S. alterniflora could be described as a function of the depth below mean high high water (MHHW), which controls inundation frequency and duration (i.e., the hydroperiod). Here we follow the findings of Morris et al. (2002) and calculate biomass as a function of depth below MHHW:

$$B_{p} = 0 \quad D < D_{min}$$

$$B_{p} = \frac{B_{max}}{D_{max} - D_{min}} (D - D_{min}) \quad D_{min} \le D \le D_{max},$$

$$B_{p} = 0 \quad D > D_{max}$$
(11)

where B_p [dimensions M L⁻²] is the peak biomass, B_{max} [M L⁻²] is the biomass at the optimal depth below MHHW, *D* is the depth of the marsh surface below MHHW, and D_{min} and D_{max} are the minimum and maximum depths below MHHW that define the limits of macrophyte survival. The peak biomass is calculated once per year; the MHHW and depth below MHHW at the time of peak biomass from the previous year are used to determine the current year's peak biomass. This approach assumes a rapid adjustment of biomass to local factors such as the depth below MHHW based on a long-term record of biomass dynamics from the North Inlet Estuary in South Carolina (Morris and Haskin, 1990), and this assumption has been shown reasonable for other marshes (e.g., Marani et al., 2007).

The aboveground live biomass per unit area, B_{ag} [M L⁻²], varies through the seasons, peaking in the summer months (Morris and Haskin, 1990). This effect can be approximated by

$$B_{\rm ag} = \frac{1}{2} \bigg[B_{\rm min} + B_{\rm p} + (B_{\rm p} - B_{\rm min}) \cos \bigg(\frac{2\pi [jd - jd_{\rm ps}]}{365} \bigg) \bigg], \qquad (12)$$

where B_{ag} is the aboveground biomass $[ML^{-2}]$, *jd* is the julian day (e.g., Jan 1st = 1, Dec 31st = 365), *jd*_{ps} is the day of the year when aboveground biomass is at its peak and B_{min} $[ML^{-2}]$ is the minimum aboveground biomass.

Belowground biomass is related to aboveground biomass (e.g., Darby and Turner, 2008). Over 3 years, the ratio between above and belowground biomass was measured using a 'marsh organ' (Fig. 3b) at North Inlet (Fig. 3a); descriptions of the methods and apparatus involved may be found in Morris (2007a). Although the data exhibit a high degree of variability (Fig. 3c), both the mean values of the root:shoot ratio and the extremal values of this ratio decline monotonically with depth over the 3 years of field seasons. We thus approximate the ratio of root:shoot of *Spartina alterniflora* at North Inlet as a linearly decreasing function of the depth below MHHW:

$$\frac{B_{\rm bg}}{B_{\rm ag}} = \theta_{\rm bg} D + D_{\rm mbm},\tag{13}$$

where θ_{bg} and D_{mbm} are the slope $[L^{-1}]$ and the intercept [dimensionless] of the relationship between the roots:shoots ratio and the depth below MHHW.

We have based Eqs. (11)-(13) on measurements at North Inlet because of the comprehensive nature of the data set available (16 years of monthly standing biomass and growth rate measurements on a number of sites). Because we do not have similar data at other field locations, we cannot rule out the possibility that other species in other locations behave differently. Preliminary data in North Carolina and Louisiana (Morris, 2007b and unpublished data), however, suggest that these relationships are broadly applicable to widely distributed Spartina alterniflora communities, as well as Juncus roemerianus communities on the Atlantic coast of the United States. That salt marsh macrophytes likely have the highest potential for growth in an optimum intertidal elevation has been recognized for many decades (e.g., Redfield, 1972), and more recent work using remote sensing has confirmed this prior work that numerous marsh species are confined to narrow elevation bands within salt marshes (e.g., Silvestri and Marani, 2004; Morris et al., 2005). Further, simple models suggest that competition between species with different optimal marsh elevations can strongly influence marsh zonation (Morris, 2006, 2007c).

Following the approach of Morris and Bowden (1986) and Rybczyk et al. (1998), we describe the growth of belowground





Fig. 3. (a) Location map of the North Inlet estuary and the Goat Island and Oyster Landing within the estuary. (b) Photograph of the 'marsh organ' apparatus. (c) Roots:shoots ratio as a function of depth below MHHW at North Inlet. Data were collected following the methodology of Morris (2007a). Rows of tubes are spaced at ~15 vertical centimeters. The small variations in elevation for given rows (e.g., at ~0.3 m depth below MHHW) are due to sea-level rise over the period of data retrieval (the marsh organ was not moved over this interval). One outlier (at depth below MHHW = 0.46 m, root:shoot ratio = 13.1, taken 2006) was removed because, although this had a root mass consistent with the other samples, the surface vegetation died, giving an anomalously high root:shoot ratio. If included in the analysis the regressed values of $\theta_{\rm bg}$ and $D_{\rm mbm}$ change to -5.4 and 4.7, respectively.

biomass being greatest near the surface, and decreasing exponentially with depth:

$$b_{\rm bg} = b_0 \, \mathrm{e}^{-d/\gamma},\tag{14}$$

where b_{bg} [M L⁻³] is the belowground biomass per unit volume, b_0 [M L⁻³] is the belowground biomass per unit volume at the surface of the marsh, and γ [L] is the depth over which the root growth is reduced by a factor of e^{-1} . The total belowground biomass per unit area, B_{bg} [M L⁻²], is related to the local biomass by:

$$B_{\rm bg} = \int_0^\infty b_{\rm bg} \, \mathrm{d}d. \tag{15}$$

Using Eq. (15), the biomass at the surface may be calculated for a given total biomass:

$$b_0 = \frac{B_{\rm bg}}{\gamma}.$$
 (16)

During each time step, the total growth of belowground biomass is calculated based on B_p and Eqs. (12) and (13); this total biomass is then converted to depth-dependent biomass by combining Eqs. (14) and (16).

Throughout the year, both aboveground and belowground biomasses are produced through plant growth. The change in live biomass is due to both growth and mortality of marsh macrophytes:

$$\frac{\partial B_{\rm ag}}{\partial t} = G - M. \tag{17}$$

Based on a long-term record of biomass dynamics from the North Inlet estuary in South Carolina (Morris and Haskin, 1990), we assume that the growth of aboveground biomass can be approximated by:

$$G_{ag} = \frac{1}{2} \left[G_{min} + G_p + (G_p - G_{min}) \cos\left(\frac{2\pi \left[jd - jd_{ps} + \phi\right]}{P}\right) \right]$$
(18)

where G_{ag} [ML⁻²T⁻¹] is the rate of aboveground biomass production per unit area, G_{min} [ML⁻²T⁻¹] is the minimum growth rate, G_p [ML⁻²T⁻¹] is the peak growth rate, ϕ is the phase shift (in days) and *P* is the period of the cycle, assumed to be 365 days. The phase shift term occurs because the peak growth rate occurs some days before the date of peak biomass. The mortality rate is therefore calculated by subtracting the derivative of Eq. (12) from Eq. (18). The ratio of aboveground to belowground mortality is assumed to scale with the ratio of aboveground to belowground biomass. Both belowground growth and mortality are assumed to decrease exponentially with depth (e.g., similar to root mass as described in Eq. (14)); the local belowground mortality rate is quantified using a relationship equivalent to Eqs. (15) and (16). The minimum aboveground biomass, peak growth rate, and minimum growth rate are all proportional to the peak aboveground biomass:

$$B_{\min} = \theta_{B_{\min}} B_{\rm p}, \tag{19a}$$

$$G_{\rm p} = \nu_{G_{\rm p}} B_{\rm p}, \tag{19b}$$

and

$$G_{\min} = v_{G_{\min}} B_{\rm p}, \tag{19c}$$

where $\theta_{B_{\min}}$ is dimensionless and ν_{G_p} and $\nu_{G_{\min}}$ are of dimension T⁻¹. In order to quantify the mass of carbon deposited in the soil, the mortality must be integrated with respect to time. Upon integration over an entire year we find that the total mass deposited in the marsh column is:

$$AMC = \frac{P}{2}B_{\rm p}\Big(\nu_{G_{\rm p}} + \nu_{G_{\rm min}}\Big),\tag{20}$$

where *AMC* is the annual mass of carbon deposited. Eq. (20) is included for reference; during simulations the deposition rate varies throughout the year (Eq. (17)).

3.1.2. Decay of organic carbon

Each year, both roots and shoots die and are subject to decomposition. We separate the organic carbon into labile and refractory pools. Here we model the decay of labile pools with a linear model, and the production of the pools is controlled by the mortality of both roots and stems:

$$\frac{\partial C_{\rm lfa}}{\partial t} = -k_{\rm lfa}C_{\rm lfa} + m\chi_{\rm lfa}, \qquad (21a)$$

$$\frac{\partial C_{\rm lsl}}{\partial t} = -k_{\rm lsl}C_{\rm lsl} + m\chi_{\rm lsl}, \qquad (21b)$$

and

$$\frac{\partial C_{\text{ref}}}{\partial t} = m\chi_{\text{ref}},\tag{21c}$$

where C [ML⁻³] is the organic carbon per unit volume, m [ML⁻³T⁻¹] is the mortality rate per unit volume and is related to the total mortality rate (M) using a relationship of the same form as Eq. (15), and the subscripts Ifa, Isl, and ref refer to the two labile pools and the refractory pool, as in Section 2. Decay rates depend on a number of factors, including (possibly) sulfate concentration and oxygen supply (e.g., Silver and Miya, 2001); many of the factors proposed to control the rate of organic matter decay vary with the depth below the sediment surface. Some authors have suggested depth-dependent decay coefficients (Conn and Day, 1997; Rybczyk et al., 1998). Others, however, have conducted measurements of decay in marsh sediment that show no depth dependence (e.g., Blum, 1993). Here we describe the decay coefficients as:

$$k_{\rm lsl} = k_{\rm lsl,0} \, {\rm e}^{-d/\mu_{\rm lsl}},$$
 (22a)

and

$$k_{\rm lfa} = k_{\rm lfa,0} \, \mathrm{e}^{-d/\mu_{\rm lfa}},$$
 (22b)

where $k_{\rm lsl,0}$ and $k_{\rm lfa,0}$ [T⁻¹] are the decay coefficients at the surface and μ [L] is a length scale over which the decomposition rate decreases with depth. In the case of decomposition that does not depend on depth, μ approaches infinity.

3.2. Inorganic sedimentation

During tidally induced floods, suspended sediment can be advected from marsh creeks onto the marsh platform. This sediment may subsequently be deposited through either settling or trapping by marsh vegetation. Inorganic sedimentation due to both settling and trapping is a function of the depth of the marsh surface below mean high tide because with increasing depth the marsh surface is inundated and exposed to sediment laden water for greater periods. In the OIMAS-N model, a linear relationship between the time the marsh is inundated and the sedimentation rate is used. Sedimentation also varies linearly with the concentration of suspended sediment in the waters that flood the marsh (e.g., Mudd et al., 2004). Trapping is calculated using the methodology of Palmer et al. (2004) as implemented by D'Alpaos et al. (2006). For trapping, we use a reference velocity of 1 cm s⁻¹. Preliminary numerical experiments have demonstrated that flow velocity has little impact on the inorganic sedimentation rate; accretion rates due to trapping are approximately two orders of magnitude less than rates due to settling unless the reference velocity is unrealistically high (e.g., >0.5 m s⁻¹). During each time step the total inundation time is calculated based on the tidal amplitude and the elevation of the marsh surface. This inundation time is then multiplied by the settling velocity and the concentration of the suspended sediment in the water above the sediment column.

The OIMAS-N model is intended to be flexible and can accommodate storm erosion by removing sediment from the top of the marsh column. For example, storm erosion could be calculated using a formulation based on excess shear stress (e.g., D'Alpaos et al., 2007; Marani et al., 2007). In this manuscript, however, we focus on depositional processes. Storm erosion is typically focused near open water and the banks of marsh creeks (e.g., van de Plassche et al., 2006), and due to the damping effect of vegetation on storm waves (e.g., Moller, 2006), storms typically result in deposition in the interiors of coastal salt marshes (e.g., Goodbred and Hine, 1995; Leonard et al., 1995; Yang et al., 2003; Cahoon, 2006).

3.3. Compaction

The sediments that make up salt marsh platforms are compressible. Compaction may play a significant role in determining the absolute elevation of marsh surfaces (e.g., Cahoon et al., 1995; Long et al., 2006; Turner et al., 2006). Here we use a constitutive equation verified by numerous laboratory compaction tests (e.g., Gutierrez and Wangen, 2005):

$$E = E_0 - CI \log\left(\frac{\sigma_{\rm eff}}{\sigma_0}\right). \tag{23}$$

Here E [dimensionless] is the void ratio, CI [dimensionless] is the compression index, E_0 [dimensionless] is the void ratio at the reference stress, σ_0 [M T⁻² L⁻¹], and $\sigma_{\rm eff}$ [M T⁻² L⁻¹] is the effective stress. It is assumed the column is under hydrostatic pressure; because the modeled columns are on the order of meters in depth it is assumed excess pore pressure diffuses rapidly relative to the rate of sedimentation. Because of the hydrostatic assumption, the effective stress at any depth below the surface is simply the buoyant weight of the material above it. The compression index and reference void ratio depend on the substrate. For sand we set CI = 0.1, $\sigma_0 = 10^5$ pa, and $E_0 = 0.6$ and for silt we set CI = 0.2, $\sigma_0 = 10^5$ pa, and $E_0 = 0.4$. These values lie within the range of natural variability for these substrates. Organic material has been found to be far more compressible than inorganic material (e.g. Mesri et al., 1997). Thus for organic matter we set CI = 1.0, $\sigma_0 = 10^4$ pa, and $E_0 = 0.25$.

4. Simulations

Both field studies (e.g., Delaune et al., 1989; Temmerman et al., 2003; Chmura and Hung, 2004) and modelling studies (e.g., Mudd et al., 2004; Temmerman et al., 2005; D'Alpaos et al., 2007; Kirwan and Murray, 2007) have demonstrated that the supply of inorganic sediment decreases as a function of distance from marsh creeks. Thus the spatial distribution of inorganic sediment supply to the marsh surface should be expected to be heterogeneous. At the same time, if a marsh is to remain in equilibrium with sea-level rise the entire marsh must accrete at the same rate, by definition. Thus to maintain accretion that keeps pace with sea-level rise the

preservation of organic material in the marsh column, through the increased deposition of refractory carbon, must offset the reduction in inorganic sedimentation as one moves away from the marsh creek.

In this section we perform a series of numerical simulations in order to explore the adjustment of marsh stratigraphy to changing rates of sea-level rise and changing rates of inorganic sediment supply. In order to perform this analysis, parameters for the simulations must be chosen. Each parameter in the OIMAS-N model can be quantified independently, but we know of no marsh where such data exist. In order to test the model, we examine its ability to reproduce marsh stratigraphy that has been measured in the field. We have chosen to test the model using data from the North Inlet Estuary, in South Carolina, USA. We choose this location to test the model because it has, to our knowledge, the most comprehensive set of data that is required to run the OIMAS-N model. At North Inlet, all but four of the required OIMAS-N model parameters have been measured independently; we use core data from North Inlet to calibrate these four unknown parameters. We then use the calibrated parameters to run simulations used to examine the relationship between sediment supply, the rate of sealevel rise, and organic carbon accumulation on salt marshes.

4.1. Growth characteristics at North Inlet

North Inlet is a Long Term Ecological Research (LTER) site, and the stand characteristics of *Sparting alterniflora*, including standing biomass and growth rates have been monitored for a number of vears. The methodology and location of these measurements is described in Morris and Haskin (1990). Here we present a longterm record for the growth rate as a function of peak annual biomass for eight individual plots located at two unfertilized low marsh sites at North Inlet: Oyster Landing and Goat Island (Fig. 3a). The eight plots have data spanning either 1986-2002 or 1987-2002, and there are 195 measurements in total. From these data we have determined ν_{G_p} and $\nu_{G_{min}}$ (Fig. 4a). For each year we also recorded the date of both the peak standing biomass and the peak growth rate, and from these data we determined the average phase shift, ϕ . Due to both natural variability and the fact that sampling occurred, on average, once a month in each of the eight plots, there is a high degree of variability in the phase shift data (Fig. 4b). For this reason our value for phase shift should be considered an approximation. We regard this uncertainty as tractable however, as the annually averaged organic deposition is more strongly dependent on the maximum growth rate than on the phase shift, and the maximum growth rate is reasonably well constrained by the field measurements (Fig. 4a).

4.2. Calibration of parameters at North Inlet

A large number of the parameters for the OIMAS-N model have been measured independently (that is, not calibrated using the model) at North Inlet (Table 1). We do, however, find it necessary to calibrate several parameters that have not been independently measured at the site. The parameters needing calibration are the settling characteristics of the suspended sediment, the e-folding depth of root growth (γ , i.e., the depth at which the root growth declines by a factor of 1/e), the decay rate of labile organic carbon, and the percentage of organic matter deposited on the marsh that is labile carbon vs. refractory carbon. Of these parameters, we expect several of them to fall within a relatively tight range. For example, measured carbon decay rates on salt marshes tend to fall within a relatively narrow band between 0.2 and 0.8 yr⁻¹ (e.g., Morris and Bowden, 1986; Blum, 1993; Conn and Day, 1997; Rybczyk et al., 1998), and root depth tends to be on the order of



Fig. 4. (a) The Growth rate as a function of Peak Biomass for Goat Island (N = 99) and Oyster Landing (N = 96) low marsh sites. Each site consists of four separate plots. Linear regressions for each site are shown on chart, there is no statistical difference between plots at the same site. Regression of all the data has $\nu_{G_p} = 0.0138 \text{ day}^{-1}$ with $R^2 = 0.76$. (b) Cumulative probability plot of the phase shift, ϕ . Stepped nature of the figure is due to the field sampling on a monthly interval. The average phase shift is 56 days.

several decimeters (e.g., Morris and Bowden, 1986). We also vary the effective settling velocity, v_{eff} , of the sediment during the simulations.

Our calibration uses published data on organic matter percentage as a function of depth for a core taken at North Inlet by Sharma et al. (1987). We use the parameter values listed in Table 1, and vary the four unknown parameters. The carbon profiles generated by the OIMAS-N model are then compared to published data by quantifying the root mean square error (*RMSE*) between the measured and predicted organic carbon percentage:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n} \left(O_{\text{measured},i} - O_{\text{modeled},i}\right)^2\right]^{1/2},$$
(24)

where *O* is the percent organic matter, and *n* is the number of samples in the core. To produce the modeled cores, we allow a sediment column to develop at an accretion rate of 0.27 cm yr⁻¹, the long-term rate determined by Vogel et al. (1996). There is some indication that accretion rates have been variable over the last 150 years (Sharma et al., 1987), but we do not attempt to capture this variability. Because of this, our simulations are not able to exactly reproduce the ²¹⁰Pb profiles measured by Sharma et al. (1987), but

 Table 1

 Parameter values used in simulations

Parameter	Value	Source
Tidal amplitude	0.7 m	Morris et al. (2002)
D _{max}	0.55 m	Based on data from
		Morris et al. (2002)
D _{min}	0.0 m	Based on data from
		Morris et al. (2002)
B _{max}	$2500 \mathrm{g}\mathrm{m}^{-2}$	Based on data from
		Morris et al. (2002)
B _{min}	$0 \mathrm{g} \mathrm{m}^{-2}$	Based on data from
		Morris et al. (2002)
ν_{G_p}	$0.0138 \mathrm{day}^{-1}$	This study (Fig. 4a)
$v_{G_{\min}}$	0.0 day ⁻¹	This study (Fig. 4a)
φ	56 days	This study (Fig. 4b)
θ_{bg}	-6.8 m^{-1}	This study (Fig. 3c)
D _{mbm}	4.8 (dimensionless)	This study (Fig. 3c)
Total suspended	$30 \text{ mg } l^{-1}$	Gardner et al. (2006)
sediment concentration		note: value rounded
		from 28.47

the rate of sea-level rise we use is the best-fitting rate if constant sea-level rise is assumed. It is not our purpose to exactly reproduce the data of Sharma et al. (1987), but rather to find physically realistic approximations of the unknown parameters that can be used to test the sensitivity of coastal salt marsh stratigraphy to sediment supply and the rate of sea-level rise. We find, upon visual inspection of predicted profiles, that a number of parameter combinations can be dismissed as unrealistic (see below), whereas out best estimate of the four parameter values results in an *RMSE* of less than 1% organic matter in the core. The minimum *RMSE* for the core has been quantified based on a large number of simulations (N = 1554). We are thus confident that the calibrated parameter values lie within the range of natural variability at North Inlet.

The best-fit estimate of the calibrated parameters is shown in Fig. 5, plotted with the data of Sharma et al. (1987). Modification of these parameters can lead to large changes in the predicted pattern of organic composition as a function of depth. We demonstrate the effect of changing the four parameters in Fig. 6; a range of parameter combinations produce predicted organic matter profiles that clearly diverge from the patterns measured by Sharma et al. (1987). When roots die, the fraction of the root mass that becomes refractory carbon is χ_{ref} (Equation 21c). Varying this parameter changes the organic carbon content in the profile at depth, but does



Fig. 5. Best-fit prediction of % organic matter as a function of depth (grey squares) using the OIMAS-N model plotted with data collected by Sharma et al. (1987) at Bread and Butter Creek, North Inlet, SC (black crosses). The *RMSE* of the organic carbon % is 0.68.

not affect the near-surface peak in organic content (Fig. 6a). Varying the effective settling velocity (v_{eff}) changes the distribution of percent carbon in the column (Fig. 6b). Varying both the e-folding depth of root growth (γ) and the labile carbon decay coefficient (k) changes the near-surface peak of carbon content but not the carbon content at depth (Fig. 6c,d). In general, the carbon content approaches a constant value at depth. This is because all labile carbon is consumed by decay processes. Thus there is a layer of sediment, near the surface, where labile carbon is still present. We find that the variation in the four calibrated parameters does not lead to differences in the depth of the sediment in which labile carbon was still present. This includes variation in the e-folding depth of root growth. Five simulations were performed to examine the sensitivity of the carbon profile to changes in the rate of SLR (Fig. 6e). We find that changing the rate of SLR can change both the carbon content of the profile and the depth over which labile carbon is present.

4.3. Effect of the rate of sea-level rise and sediment supply on marsh stratigraphy

Using the parameters both measured independently (Table 1) and calibrated using a core from North Inlet (Table 2), we have performed a series of simulations examining the effect of changing rates of sea-level rise and sediment supply on the stratigraphy and carbon accumulation in a coastal marsh with characteristics similar to North Inlet. While the model is generally applicable, we use the parameters tested for North Inlet because we know, based on model testing, that they lie within the range of natural variability of coastal salt marshes.

At low rates of sea-level rise, the rate of refractory carbon accumulation increases with a rise in rate of sea-level rise, the total labile stored in the marsh increases (the accumulation of this carbon is zero because it all must decay), and the percent of deposited sediments that are made of organic material also increases. Carbon accumulation does not increase indefinitely with increasing seal-level rise, however. As described by Morris et al. (2002), for a given sediment supply there is a maximum rate of sealevel rise that a marsh can keep pace with before it drowns (that is, the marsh surface becomes too deep relative to MHHW for plant survival). A number of our OIMAS-N model runs resulted in drowned marshes; this is why data corresponding to rapid sealevel rise ($\geq 8 \text{ mm yr}^{-1}$) are confined to relatively high suspended sediment concentrations (Fig. 7). For example, marshes with a rate of SLR of 8 mm yr⁻¹ and a suspended sediment concentration of 10 mg l^{-1} will drown.

Carbon dynamics are also sensitive to inorganic sediment supply (Fig. 7). As the supply of suspended sediment decreases, the rate of refractory carbon accumulation increases, the total labile carbon stored in the marsh increases, and the percent of deposited sediments that are made of organic material also increases. For example, increasing the sediment supply from 1 to 10 mg per liter reduces the total labile carbon stored in the marsh sediment from 80 to 30 kg per square meter of surface area. This effect is particularly strong in marshes with relatively low sediment supply. Thus, carbon dynamics of marshes in sediment poor regions are especially sensitive to a disturbance in sediment supply, be it due to anthropogenic or other factors. We also note that suspended sediment should decrease rapidly as a function of distance from the marsh creek (e.g., Leonard et al., 2002; Temmerman et al., 2003; Chmura and Hung, 2004) so it is likely that the percentage of carbon in sediment stored near marsh creeks will be lower than at locations in the interior of the marsh, as will perhaps the absolute storage of carbon, depending on the rate of sea-level rise and equilibrium marsh elevation.



Fig. 6. A series of simulated profiles of % organic matter demonstrating the effect of varying the calibrated model parameters. (a) Variable initial fraction refractory carbon, all else held constant. (b) Variable effective settling velocity. (c) Variable rate coefficient of labile carbon decay. (d) Variable e-folding depth of root growth. (e) Variable rate of sea-level rise.

The OIMAS-N model predicts rates of carbon accumulation that are consistent with those reported by Chmura et al. (2003), Choi and Wang (2004) and Neubauer et al. (2002) for a range of sites. Chmura et al. (2003), using data compiled from a number of

Table 2

Best-fit of parameters to profile at Bread and Butter Creek collected by Sharma et al. (1987).

Parameter	Value
γ	0.11 m
k _l	$0.2 \ yr^{-1}$
v _{eff}	0.037 mm s^{-1}
χref	0.158

sources, reported carbon accumulation rates of marshes with mean annual temperatures between 15 °C and 20 °C (the approximate annual temperature of North Inlet is 17 °C) that ranged between 0 and 0.8 kg m⁻² yr⁻¹, with one outlier at 1.7 kg m⁻² yr⁻¹. Morris et al. (2002) reported an acceleration in the rate of sea-level rise at North Inlet from 2.7 mm yr⁻¹ prior to 1984, to 4.0 mm yr⁻¹ from 1984 to 1996, and again to 16.4 mm yr⁻¹ since 1996. With these rates of sea-level rise the OIMAS-N model predicts carbon accumulation rates of 0.4 kg m⁻² yr⁻¹ and 0.7 kg m⁻² yr⁻¹, respectively. The OIMAS-N model also predicts that the marsh will drown at current rates of sea-level rise (16.4 mm yr⁻¹), consistent with the findings of Morris et al. (2002).

b

100

80

60

40

20

0

0

50

carbon of deposited sediment

%

200

150

100

Suspended sediment

labile carbon not included)

concentration (mg L⁻¹) concentration (mg L⁻¹) С d 0.6 60 **Depth below MHHW** of marsh surface (m) total labile carbon in column (kg m⁻²) 0.4 40 0.2 20 0 0 100 150 200 0 100 150 200 0 50 50 Suspended sediment Suspended sediment concentration (mg L⁻¹) concentration (mg L⁻¹)

Fig. 7. Supply of refractory carbon (a), carbon content of accumulating sediment (b), total labile carbon (c), and the equilibrium depth below MHHW of the marsh surface (d) under a range of rates of sea-level rise and inorganic sediment supply rates. Parameter values for simulations are shown in Tables 1 and 2.

We also performed exploratory simulations that included depth-dependent decay of labile carbon. Studies of carbon decay rates at different depths have been inconclusive in coastal environments (e.g., Conn and Day, 1997), yet depth-dependent decay is common in terrestrial environments and has been incorporated into many models of soil carbon turnover (e.g., Baisden and Amundson, 2003; Jenkinson and Coleman, 2008). A reduction in

а

rate of refractory carbon accumulation (kg m⁻² yr⁻¹) 2.5

2.0

1.5

1.0

0.5

0

0

50



Fig. 8. Effect of depth-dependent decay on the amount of labile carbon stored in the sediment column as a function of suspended sediment concentration. Solid lines are for marsh columns with no depth-dependent decay, dotted lines are for marshes with depth-dependent decay.

carbon decay rates with depth is likely related to, amongst other factors, the saturation state of the sediments, so we selected an e-folding depth in the reduction of carbon decay rates that is of the same order as the tidal amplitude: $\mu = 0.4$ m. Introducing depth-dependent decay, common in terrestrial soils but unconstrained in marsh sediment, has a significant effect on the amount of labile carbon stored in the marsh (Fig. 8). If one takes the frame of reference of deposited organic carbon, this carbon moves downward in the marsh column as sediment is deposited above it. The faster the rate of marsh accretion, the more rapidly this carbon moves to greater depth. If the rate of sea-level rise is rapid and carbon experiences depth-dependent decay, labile carbon can be preserved by advecting it below the zone where decay is most intense (Fig. 8).

5. Conclusions

Organic sedimentation can play an important role in maintaining the elevation of coastal salt marshes. Feedbacks exist between marsh elevation and sedimentation, both for inorganic sediment (higher elevation results in less flooding and exposure to suspended sediment) and organic sediment (higher elevation results in lower biomass and less root growth, but a higher root:shoot ratio). We have explored the tension between organic and inorganic sedimentation in salt marshes experiencing sea-level rise using both an analytical and numerical model. The analytical model, OIMAS-A, demonstrates the importance of understanding the organic fraction of marsh sediments when using isotope dating methods (¹³⁷Cs and ²¹⁰Pb) to estimate marsh accretion. Turner et al. (2006) observed that in a large number of reported marsh cores,

rate of sea

level rise

1 mm yr⁻ 2 mm yr⁻

4 mm yr⁻ 8 mm yr⁻

16 mm yr 32 mm yr

200

150

100

Suspended sediment

the accretion rate determined by ¹³⁷Cs outpaced the accretion rate estimated by ²¹⁰Pb. We have demonstrated how this effect is potentially a result of organic decomposition. A key component of the difference in estimated accretion rates using these two radioisotopes is the relative depth over which they are measured; organic decomposition most strongly affects radioisotope concentrations near the marsh surface. These results emphasize the need to report the concentrations of organic matter in profiles that are subject to radioisotope analysis.

The numerical model (OIMAS-N) has been constructed to capture a richer array of belowground processes than the OIMAS-A model. A large fraction of this model's subcomponents are general. One subcomponent that requires more study is the relationship between biomass and depth below MHHW. We have tested the OIMAS-N model at North Inlet Estuary, in South Carolina, USA, because at this location there exists a continuous, 16-year data set of monthly measurements of macrophyte growth rates and standing biomass on a number of sites, in addition to a wide range of other measurements of OIMAS-N model parameters. We expect parameter values of Eqs. (11) and (13) to vary between species and geographic locations, but we cannot rule out that different species have different functional relationships between biomass, growth and depth below MHHW. Several lines of evidence, including preliminary data from marsh organ experiments (Morris, 2007b) and the well-defined elevation bands of many marsh species (e.g., Silvestri and Marani, 2004; Morris et al., 2005) do suggest that the model may be extended to other species. Thus, we urge more research in this area.

The OIMAS-N model was then used to investigate how sediment supply and sea-level rise affect marsh stratigraphy, and in particular, carbon storage. The model predicts rates of carbon accumulation in the marsh that are consistent with field measurements of carbon accumulation rates reported by others. On a marsh with characteristics similar to North Inlet, the model predicts an increase in carbon accumulation from 0.4 to 0.7 kg m⁻² yr⁻¹ in response to accelerated sea-level rise from 2.7 to 4.0 mm yr⁻¹. On marshes with low sediment supplies or high rates of sea-level rise, carbon accumulation on marshes that are sediment poor are more sensitive to changes in sediment supply than sediment-rich marshes. Thus anthropogenic disturbance to sediment supplies in sediment poor marshes could dramatically change carbon accumulation rates.

Acknowledgements

Funding for this study was provided by the NOAA project 'Ecological effects of sea-level rise on coastal North Carolina marshes'. This work has made use of the resources provided by the Edinburgh Compute and Data Facility (ECDF; http://www.ecdf.ed. ac.uk/). The ECDF is partially supported by the eDIKT (http:// www.edikt.org) initiative. We thank four reviewers for their help-ful comments.

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