Estuaries Vol. 25, No. 5, p. 985–998 October 2002

Estimating the Potential for Submergence for Two Wetlands in the Mississippi River Delta

J. M. RYBCZYK[1,*] and D. R. CAHOON[2,†]

[1] *Huxley College of the Environment, Western Washington University, Bellingham, Washington 98225*

[2] *U.S. Geological Survey, National Wetlands Research Center, 700 Cajundome Boulevard, Lafayette, Louisiana 70506*

ABSTRACT: We used a combined field and modeling approach to estimate the potential for submergence for one rapidly deteriorating (Bayou Chitigue Marsh) and one apparently stable (Old Oyster Bayou Marsh) saltmarsh wetland in coastal Louisiana, given two eustatic sea level rise scenarios: the current rate (0.15 cm year^{-1}); and the central value predicted by the Intergovernmental Panel on Climate Change (48 cm by the year 2100). We also used the model to determine what processes were most critical for maintaining and influencing salt marsh elevation including, mineral matter deposition, organic matter production, shallow subsidence (organic matter decomposition + primary sediment compaction), deep subsidence, and sediment pulsing events (e.g., hurricanes). Eight years of field measurements from feldspar marker horizons and surface elevation tables revealed that the rates of vertical accretion at the Bayou Chitigue Marsh were high (2.26 (0.09) cm yr^{-1} (mean ± SE)) because the marsh exists at the lower end of the tidal range. The rate of shallow subsidence was also high (2.04 (0.1) cm yr^{-1}), resulting in little net elevation gain (0.22 (0.06) cm yr^{-1}). In contrast, vertical accretion at the Old Oyster Bayou Marsh, which is 10 cm higher in elevation, was 0.48 (0.09) cm yr^{-1}. However, there was a net elevation gain of 0.36 (0.08) cm yr^{-1} because there was no significant shallow subsidence. When these rates of elevation gain were compared to rates of relative sea level rise (deep subsidence plus eustatic sea level rise), both sites showed a net elevation deficit although the Bayou Chitigue site was subsiding at approximately twice the rate of the Old Oyster Bayou site (1.1 cm yr^{-1} versus 0.49 cm yr^{-1} respectively). These field data were used to modify, initialize, and calibrate a previously published wetland soil development model that simulates primary production and mineral matter deposition as feedback functions of elevation. Sensitivity analyses revealed that wetland elevation was most sensitive to changes in the rates of deep subsidence, a model forcing function that is difficult to measure in the field and for which estimates in the literature vary widely. The model also revealed that, given both the current rate of sea level rise and the central value estimate, surface elevation at both sites would fall below mean sea level over the next 100 years. Although these results were in agreement with the field study, they contradicted long term observations that the Old Oyster Bayou site has been in equilibrium with sea level for at least the past 50 years. Further simulations showed that the elevation at the Old Oyster Bayou site could keep pace with current rates of sea level rise if either a lower rate for deep subsidence was used as a forcing function, or if a periodic sediment pulsing function (e.g., from hurricanes) was programmed into the model.

Introduction

Insufficient sedimentation, coupled with high rates of relative sea level rise (i.e., land subsidence plus eustatic sea level rise), are two important factors contributing to wetland loss in coastal Louisiana (Boesch et al. 1994; Kuhn and Mendelssohn 1999). The eustatic sea level rise (ESLR) component of relative sea level rise (RSLR) is expected to accelerate over the next 100 years (Gornitz 1995; Church et al. 2001). To be sustainable given rising water levels, wetlands must accrete vertically at a rate that equals RSLR. A recently developed field technique that uses a sediment marker horizon in conjunction with a surface elevation table (SET), an instrument that measures changes in elevation relative to a shallow subsurface datum, has made it possible to partition and measure several of the factors that affect wetland elevation relative to sea level, including vertical accretion and shallow subsidence (Cahoon et al. 1995, 1998, 1999). Shallow subsidence is defined here as the subsurface collapse in the first two or three meters of the soil or sediment due to organic matter decomposition and primary compaction. Most estimates of RSLR reported in the literature consider only deep subsidence and ESLR even though rates of shallow subsidence can greatly exceed the rates of either of these processes in some marshes (Cahoon 1995 et al.). With the types of data now being generated from SETs and horizon markers, it is possible to

---

[*] Corresponding author: tele: 360/650-2081; fax: 360-650-7284; e-mail: john.rybczyk@wwu.edu.

[†] Current address: U.S. Geological Survey, Patuxent Wildlife Research Center, 11510 American Holly Drive, Laurel, Maryland 20708.

TABLE 1. Field measurements of parameters affecting wetland elevation at Old Oyster Bayou and Bayou Chitigue. The definitions of parameters 1 through 4 follow the convention described by Cahoon et al. (1995).

	Wetland Site		
Parameter	Bayou Chitigue	Old Oyster Bayou	Source
1. Surface Elevation Change	+0.22 cm yr^{-1}	+0.36 cm yr^{-1}	This Study
2. Vertical Accretion			
a. ^{210}Pb	0.53 cm yr^{-1}	0.62 cm yr^{-1}	McKee (1994)
b. ^{137}Cs	0.66 cm yr^{-1}	0.71 cm yr^{-1}	McKee (1994)
c. Feldspar marker	2.26 cm yr^{-1}	0.48 cm yr^{-1}	This Study
3. Shallow Subsidence	2.04 cm yr^{-1}	0.12 cm yr^{-1}	This Study
4. Deep Subsidence[1]	*1.17–1.19 cm yr^{-1}*	1.22 cm yr^{-1}	Penland et al. 1988
		0.92 cm yr^{-1}	Turner 1991
	0.85 cm yr^{-1}	0.35 cm yr^{-1}	Kemp et al. 1999
		0.7 cm yr^{-1}	Boesch et al. 1983
5. Elevation Above Mean Sea Level	0 cm	10–15 cm	Cahoon et al. (1995)
6. Above Ground NPP[2]	798 g d.w. m^{-2}	987 g d.w. m^{-2}	U.S.G.S. data (unpub.)

[1] Estimates for regional deep subsidence vary widely (see text for explanation). In this table we list the range of values reported in the literature. The italicized values are those used for model calibration.

[2] Measured as maximum aboveground biomass.

identify those coastal wetlands most vulnerable to increasing sea levels by directly comparing current and predicted rates of RSLR (ESLR + deep subsidence) and shallow subsidence to rates of vertical accretion (Cahoon et al. 1999; Day et al. 1999).

From 1992–1997, Cahoon and others used this approach to measure the factors that affect wetland elevation at Bayou Chitigue and Old Oyster Bayou (Cahoon et al. 1995, 1998, 1999), two coastal marshes subject to high rates of RSLR (Table 1) in the Mississippi River Delta plain (Fig. 1). The published 2-, 3-, and 5-year records of elevation and vertical accretion data from these two sites suggest that the potential for submergence is high for the Bayou Chitigue marsh and low to moderate for the Old Oyster Bayou marsh.

For several reasons, these types of comparisons and predictions must be viewed with some caution. Short-term field measurements of vertical accretion and shallow subsidence (due to the decomposition of organic matter and primary sediment compaction) do not necessarily integrate long-term processes that affect wetland elevation, such as compaction, decomposition, and pulsing events. Even field programs that span a decade or more may not capture infrequent sediment depositional events, such as hurricanes or river floods, that have been shown to be of critical importance for maintaining wetland elevation (Day et al. 1995). These types of measurements also do not take into account possible elevation feedback mechanisms that affect the processes themselves. A change in elevation typically alters flooding patterns that can in turn affect rates of sediment deposition, decomposition, and auto-

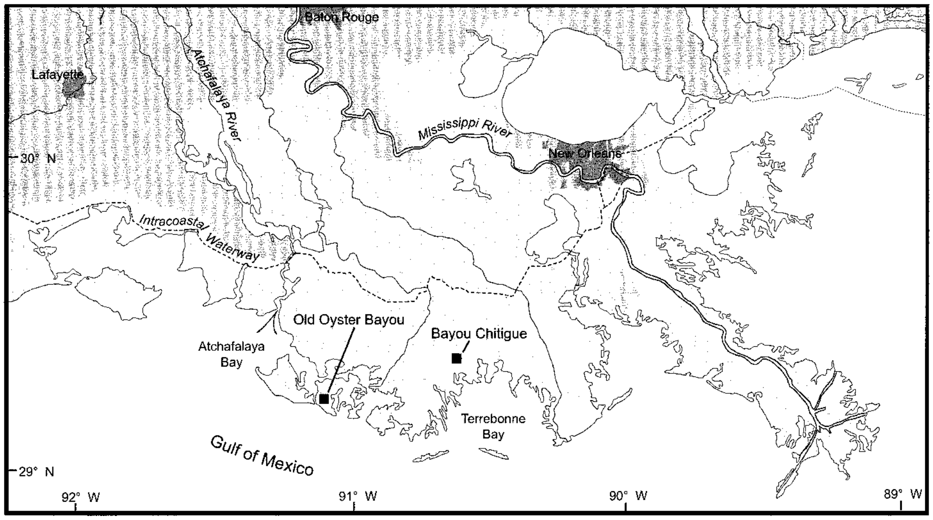


Fig. 1. Site map showing location of marshes at Old Oyster Bayou and Bayou Chitigue.

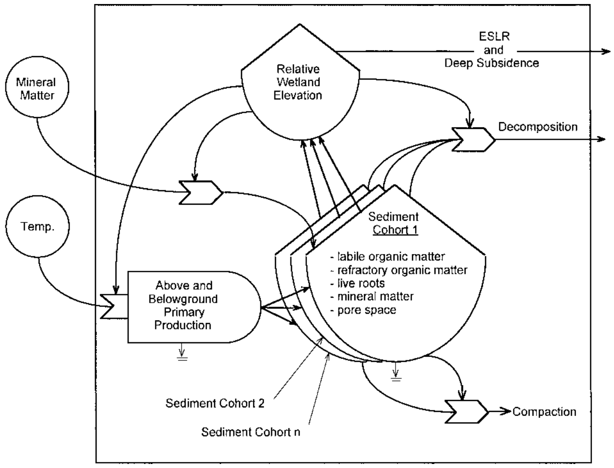


Fig. 2. An energy circuit conceptual diagram of the relative elevation model. Deep subsidence, eustatic sea level rise, and maximum mineral inputs are system forcing functions. Wetland elevation modifies primary production, mineral inputs, and decomposition. There are 18 sediment cohort layers.

genic primary production. The direct comparison of rates of relative elevation change (change due to accretion and shallow subsidence) to rates of RSLR can be problematic because of the large amount of uncertainty surrounding the measurements of both components of RSLR; deep subsidence (Turner 1991) and ESLR (Gornitz 1995).

For these reasons, site-specific computer models (Fig. 2) that consider all of the relevant processes over appropriate time scales, incorporate feedback mechanisms, and have methodologies for dealing with uncertainty (e.g., sensitivity analysis), can provide an additional and complimentary tool for examining the response of wetland elevation to increasing rates of sea level rise (Callaway et al. 1996; Rybczyk et al. 1998; Day et al. 1999). The field measurements of vertical accretion and elevation change described above not only give some indication of short-term wetland elevation dynamics but also provide data for model initialization and calibration.

In this paper we present an eight-year record (1992–2000) of field measurements of elevation change, shallow subsidence, and vertical accretion from Bayou Chitigue and Old Oyster Bayou. We use this field data to modify, initialize, and calibrate a previously published wetland elevation model (Rybczyk et al. 1998; Day et al. 1999) to predict the relationship between marsh elevation and sea level over the next 100 years. We also use the model to examine the relative importance of the processes that affect marsh elevation at the two sites. Finally, we use the model to examine the importance of pulsing events, such as hurricanes, on long-term wetland sustainability.

Methods

SITE DESCRIPTION

The wetlands adjacent to Bayou Chitigue and Old Oyster Bayou are both *Spartina alterniflora* salt marshes in the Lafourche deltaic complex (Penland et al. 1988). The marsh at Bayou Chitigue is rapidly deteriorating and is largely isolated from its original source of sediments, the Mississippi River, as a result of the construction and continued maintenance of flood control levees. Although some sediment from the Atchafalaya River may reach Bayou Chitigue via the Intracoastal Waterway (Fig. 1), most sediments deposited on this marsh are reworked from nearby bay bottoms (Murray et al. 1993). The Old Oyster Bayou marsh receives inputs of riverine sediments from the Atchafalaya River and has not undergone any substantial break up (Cahoon et al. 1995). Rates of vertical accretion, surface elevation change, shallow subsidence, deep subsidence, aboveground production, and the elevation above mean sea level (MSL) measured or estimated at the two sites are shown in Table 1.

FIELD SAMPLING

In 1992, a total of 21 marker horizon plots and three SET benchmarks were established in interior marsh areas at least 15 m from the nearest marsh channel at both Bayou Chitigue and Old Oyster Bayou. To measure accretion we collected a single soil core from each marker horizon plot on each sampling date (Fig. 3) using the cryogenic method described in Cahoon et al. (1996). For each SET benchmark, we measured nine rods at each of four sampling positions on each sampling date. A detailed description of the methods used to install and measure the SET can be found in Cahoon et al. (1995, 1999). Annual rates of vertical accretion, elevation change, and shallow subsidence were determined by regression analysis with intercepts forced through zero. Tests of significance were conducted at the $\alpha = 0.05$ level. The rate of shallow subsidence was calculated as the difference between the rate of vertical accretion and elevation change. At the end of the eight year period, replicate cores, 30 cm deep, were collected from each site and analyzed for percent mineral matter, percent organic matter, and bulk density with depth, to calibrate the wetland elevation model described below.

WETLAND ELEVATION MODELING

Model Development

The model used here is similar in framework to the mechanistic wetland soil genesis model developed by Morris and Bowden (1986) and later mod-

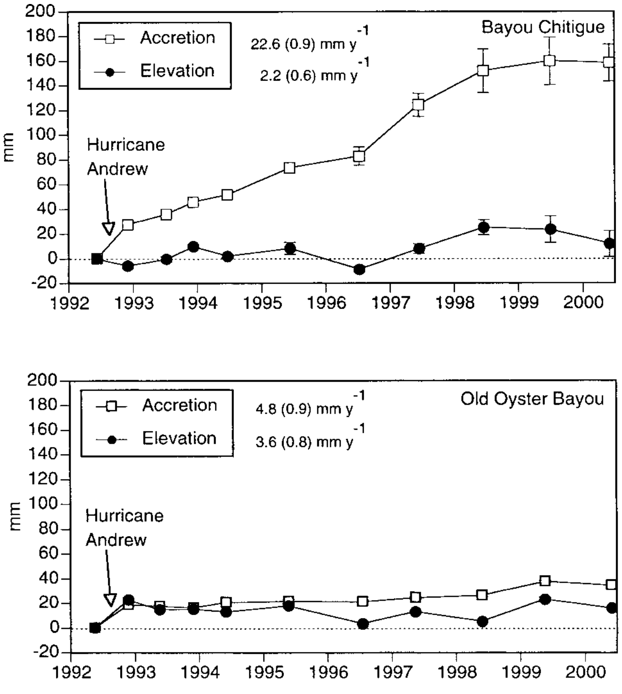


Fig. 3. Field measurements of vertical accretion and elevation change for Bayou Chitigue and Old Oyster Bayou from 1992 to 2000. Annual rates are calculated by linear regression analysis.

ified by Callaway et al. (1996) and Rybczyk et al. (1998) to simulate elevation changes in marshes subject to rising sea levels. It incorporates a mineral sediment deposition function that is derivative of the algorithms developed by Allen (1990) and French (1993), and mechanizes many of the processes related to wetland elevation that Chmura et al. (1992) simulated in one of the original wetland stability-RSLR models. A complete description of the generic model, including validation exercises, is provided in Rybczyk et al. (1998). A brief description of the model and modifications to the published model are provided in the following sections.

Model Description

The model utilizes a cohort approach (tracking discrete packages of sediments through depth and time) to simulate sediment dynamics (organic and mineral matter accretion, decomposition, compaction, and belowground productivity) (Fig. 2). These dynamics produce model-generated changes in sediment characteristics including bulk density, organic matter volume and mass, mineral matter volume and mass, and pore volume. The model yields total sediment height as an output. Sediment height is then balanced with ESLR and deep subsidence, both forcing functions, to determine wetland elevation relative to sea level. The model was programmed using STELLA iconographic modeling software (Richmond et al. 1987). An Euler numerical method, with a time step of one week, was used to solve the finite difference equations generated by the STELLA software. The model consists of three linked submodels or sectors: primary productivity; sediment dynamics; and relative elevation. State variable differential equations are described in Table 2.

Primary Productivity Submodel. Since there is no linked hydrology, hydrodynamics or salt conservation model, elevation relative to sea level acts as a surrogate for flooding stress on vegetation production in the primary production submodel. By employing a simple elevation switching function (Table 3), above- and belowground annual production decrease with decreasing elevation to simulate flooding stress (e.g., reduced energy yield during anaerobic root respiration, decreased root conductivity, sulfide toxicity; Lessmann et al. 1997).

Few studies have measured the relationship between above- and belowground net primary production (NPP) in *Spartina alterniflora* marshes and the results from the few that have are equivocal, some reporting that belowground NPP is less than aboveground NPP, some reporting higher belowground NPP, and some reporting equal rates of NPP above- and belowground (Gallagher and Plumley 1979; Schubauer and Hopkinson 1984; Gross et al. 1991; Lessmann et al. 1997). Since belowground production was not measured at either Bayou Chitigue or Old Oyster Bayou, simulated belowground production was set to equal aboveground production.

The simulated organic matter is allocated to the sediment dynamics submodel as surface litter and within the sediment soil column as root biomass. There are two state variables in this submodel, leaf (aboveground biomass) and root (belowground biomass) (Table 2). These state variables are a function of one constant, root:shoot ratio (rootmult), and four rates: net primary production (maxnet), leaf litter production during the growing season (llitrateg), leaf litter production at the end of the growing (llitrated), and root litter production (rlitrate). Litter production for both state variables is set to equal annual production.

Sediment Dynamics Submodel. The sediment dynamics submodel has four state variables (Table 2): lab_below$_n$, labile organic matter; ref_below$_n$, refractory organic matter; mineral$_n$, mineral matter; and root$_n$, live root biomass, each replicated once in each of 18 soil cohorts. The differential equations describing the changes in these state variables with time are shown in Table 2. Maximum mineral inputs are the only forcing functions in this sub-

TABLE 2. State variables and differential equations for the Integrated Wetland Elevation Model.

Labile organic matter sediment cohorts, lab_below$_n$	
d(lab_below$_n$)/dt =	(litter*leaf_lab_frac) + (rlit$_n$*rlab%) + (tranl$_{n-1}$*lab_below$_{n-1}$) − lab_below$_n$*klab) − (tranl$_n$*lab_below$_n$)
where:	
lab_below$_n$	labile organic matter in cohort n (g C cm^{-2})
litter	aboveground leaf litter inputs to surface cohort (g C cm^{-2} week^{-1})
leaf_lab_frac	labile fraction of aboveground biomass (unitless)
rlit$_n$	root litter inputs to cohort n (g C cm^{-2} week^{-1})
rlab%	labile fraction of root litter (unitless)
tranl$_{n-1}$	fraction of labile organic matter transferred from overlying cohort (unitless)
lab_below$_{n-1}$	labile organic matter in overlying cohort (g C cm^{-2})
klab	decomposition rate of labile organic matter (week^{-1})
tranl$_n$	fraction of labile organic matter transferred to underlying cohort (unitless)
Refractory organic matter sediment cohorts, ref_below$_n$	
d(ref_below$_n$)/dt =	(litter*(1 − leaf_lab_frac)) + (rlit$_n$*(1 − rlab%)) + (tranr$_{n-1}$*ref_below$_{n-1}$) − (ref_below$_n$*kref) − (tranr$_n$*ref_below$_n$)
where:	
ref_below$_n$	refractory organic matter in cohort n (g C cm^{-2})
tranr$_{n-1}$	fraction of refractory organic matter transferred from overlying cohort (unitless)
ref_below$_{n-1}$	refractory organic matter in overlying cohort (g C cm^{-2})
kref	decomposition rate of refractory organic matter (week^{-1})
tranr$_n$	fraction of refractory organic matter transferred to underlying cohort (unitless)
Mineral matter in sediment cohorts, mineral$_n$	
d(mineral$_n$)/dt =	(max_min_in*minelvfunc) + (tranm$_{n-1}$*mineral$_{n-1}$) − (tranm$_n$*mineral$_n$)
where:	
mineral$_n$	mineral matter in cohort n (g cm^{-2})
max_min_in	maximum mineral input as a function of elevation (g cm^{-2} week^{-1})
tranm$_{n-1}$	fraction of mineral matter transferred from overlying cohort (unitless)
mineral$_{n-1}$	mineral matter in overlying cohort (g cm^{-2})
tranm$_n$	fraction of mineral matter transferred to underlying cohort (unitless)
Live roots in sediment cohorts, root$_n$	
d(root$_n$)/dt =	rootin$_n$ − (rlitrate*root$_n$)
where:	
root$_n$	live root biomass in cohort n (g C cm^{-2})
rootin$_n$	fraction of total root production (root) distributed to cohort n (g C cm^{-2})
rlitrate	rate of root litter production (week^{-1})
Aboveground macrophyte biomass, Leaf	
d(leaf)/dt =	maxnet − (leaf*llitrateg) − (leaf*llitrated)
where:	
leaf	aboveground biomass (g C m^{-2})
maxnet	maximum net primary productivity (g C m^{-2} week^{-1})
llitrateg	leaf litter production rate during the growing season (week^{-1})
llitrated	leaf litter production rate during the dormant season (week^{-1})
Belowground macrophyte biomass, Root	
d(root)/dt =	rootprod − (root × rlitrate)
where:	
Root	belowground live root biomass (g C m^{-2})
rootprod	root production rate (g C m^{-2} week^{-1})
rlitrate	root litter production rate (week^{-1})

model, as other inputs are model-generated. This submodel simulates the decomposition of organic matter, the inputs of mineral matter, the distribution of root biomass, sediment compaction, and the transfer of material from cohort to cohort. These processes are outlined below. Output includes the following sediment characteristics with depth: bulk density, sediment height, organic and mineral matter mass and volume, pore space, and live root mass. Changes within the cohort caused by decomposition and belowground production, which are both a function of model-generated depth, are calculated on a weekly basis. Sediment compaction, also calculated weekly, is a function of initial pore space (a forcing function) and the mass of material above a particular cohort. Measurements obtained from soil cores (e.g., bulk density, percent organic and mineral matter) along with some measurement of accretion rates (e.g., Pb^{210} or marker horizons) provide the data that calibrate the submodel at several points. Critical algorithms for this submodel are described below.

Decomposition. The model separates all organic matter into labile or refractory pools, each with its own time dependent decay rate. The model is generic in the sense that by changing the original proportion of organic matter that is either labile or refractory, it can be used appropriately for a variety of wetland plant species. The labile organic matter decomposition rate for the surface cohort is separate from the labile decomposition rate for the rest of the cohorts (allowing for a distinction between leaf and root labile organic matter). There is a separate, depth dependent decomposition rate for deep refractory material. A simple negative exponential (−k) model describes de-

TABLE 3. Simulated vegetation biomass switching function compared to observed parameters derived from the unpublished United States Geological Survey data. Observed values are reported as means ± standard deviation. At elevations below −30 cm net primary production is zero.

If Simulated Elevation is:[1]	Then, Simulated Aboveground Annual Production is:	Observed Aboveground Annual Production at This Elevation
>10	1,000 g d.w. m^{-2}	987 ± 283 g d.w. m^{-2} (from Old Oyster Bayou)
≤ 10 and >5	750 g d.w. m^{-2}	
≤ 5 and > -15	500 g d.w. m^{-2}	798 ± 288 g d.w. m^{-2} (from Bayou Chitigue)
≤ -15 and > -30	250 g d.w. m^{-2}	

[1] cm above or below MSL.

composition for each organic matter state variable in each cohort. Required decomposition constants include kdeep, klab, kref, leaf_lab_frac, rlab%, and klabsurf, all described in Table 4.

Mineral Inputs. Although it is difficult to predict exact rates of accretion, previous models have simulated future mineral inputs as a function of marsh elevation, frequency of inundation, current sediment accumulation rates, and tidal range (French 1993; Callaway et al. 1996; Rybczyk et al. 1998). A similar approach is used here. Mineral inputs (minin) are calculated as:

$$\text{minin} = \text{max\_min\_in} * \text{minelvfunc} \tag{1}$$

where:

Max_min_in = maximum mineral input (g cm^{-2} $week^{-1}$)

minelvfunc = unitless multiplier; 1 if $\text{tidehight} \leq 0$ else $(1.0 - (\min(\text{tidehight}, 1.0)))$

and:

$$\text{tidehight} = (\text{relative\_el} - \text{msl})/(\text{tidal\_range}/2) \tag{2}$$

where:

relative_el = model simulated marsh elevation (cm)

msl = mean sea level (set to 0 cm)

tidal_range = mean tidal range (cm)

Root Distribution. Although root production is simulated in the productivity submodel, root biomass is distributed to the sediment cohorts in the sediment submodel. We used an adaptation of the distribution algorithm originally developed by Morris and Bowden (1986), where root biomass is assumed to be greatest near the surface and decreases exponentially with depth. A complete description of this function is provided in Rybczyk et al. (1998).

Sediment Compaction. Soil compaction is a func-

TABLE 4. Initialization parameters for the Relative Elevation Model.

Symbol	Description	Bayou Chitigue	Old Oyster Bayou
comp_k	half sat. constant for soil compaction	1.0 g cm^{-2}	1.0 g cm^{-2}
eslr_c	sea level rise in the next 100 years	15 cm	15 cm
init_elev	initial wetland elevation	0 cm	12 cm
kdeep	decomposition rate of deep refractory organic matter	0.00008 $week^{-1}$	0.00008 $week^{-1}$
klab	decomposition rate of labile organic matter	0.049 $week^{-1}$	0.040 $week^{-1}$
klabsurf	decomposition rate of surface labile organic matter	0.09 $week^{-1}$	0.09 $week^{-1}$
kref	decomposition rate of refractory organic matter	0.0008 $week^{-1}$	0.0015 $week^{-1}$
leaf_lab_frac	labile fraction of aboveground biomass	40%	40%
litrated	leaf litter rate during fall season	0.25 $week^{-1}$	0.25 $week^{-1}$
litrateg	leaf litter rate during growing season	0.0 $week^{-1}$	0.0 $week^{-1}$
max_min_in	maximum mineral input	0.0076 g cm^{-2} $week^{-1}$	0.0040 g cm^{-2} $week^{-1}$
maxnet	max. net aboveground production rate	24.9 g C m^{-2} $week^{-1}$ (18 weeks)	24.9 g C m^{-2} $week^{-1}$ (18 weeks)
poremax	maximum fraction of pore space in soil	86%	88%
poremin	minimum fraction of pore space in soil	84%	86%
rlab%	labile fraction of live roots	40%	50%
litrate	rate of root litter production	0.08 $week^{-1}$	0.08 $week^{-1}$
root_k	root distribution constant	0.1 cm^{-1}	0.06 cm^{-1}
rootmult	root to shoot ratio	1.0 unitless	1.0 unitless
surate	local deep subsidence rate	.023 cm $week^{-1}$	.0135 cm $week^{-1}$

tion of organic matter decomposition and the reduction of sediment pore space (primary consolidation) (Penland and Ramsey 1990). Callaway et al. (1996) simulated the compaction of pore space as an asymptotic decrease with depth, bounded by preset minimum and maximum pore space values. We use a modified version of Callaway's algorithm, where the decrease in pore space for a given cohort (pore_space_n) is a function of the mass of material above it. A complete description of this function is provided in Rybczyk et al. (1998).

Relative Elevation Submodel. Wetland elevation relative to sea level is simulated as the balance between ESLR, deep subsidence, shallow subsidence (including decomposition and compaction), and the accretion of mineral material and organic matter (via root growth and litter deposition). The balance between these factors is then added to, or subtracted from, the initial wetland elevation at the start of the simulation. The accretion of mineral matter is modeled explicitly with the minin function described in the sediment dynamics submodel. Inputs of organic matter are simulated in the primary productivity submodel. Shallow subsidence is modeled explicitly with the decomposition and pore space compaction functions described in the sediment dynamics submodel. The combination of inorganic and organic matter accretion, decomposition, and compaction result in the development of a soil column over simulated time. The total height of this column is calculated as the height of the deepest sediment cohort plus the total height of all overlying cohorts. The remaining parameters that affect simulated relative elevation, deep subsidence, and ESLR are entered into the model as forcing functions.

Model Initialization and Calibration

The data required for model initialization are shown in Table 4. For calibration we ran the model for 100 simulated years using the same rates and constants used for initialization. We then used a step-wise calibration procedure (Mitsch and Reeder 1991). The primary production submodel was calibrated first because it provided critical input to the sediment dynamics submodel. After obtaining accurate productivity simulations (simulated aboveground net primary production within one standard error of aboveground net primary production as measured in the field) we linked the submodel to the sediment dynamics submodel. The sediment dynamics submodel was calibrated with bulk density, percent organic matter, and percent mineral matter data obtained from replicate, 30 cm deep sediment cores collected in the field at each site.

Model Applications

Sensitivity Analyses. For each site, we examined the sensitivity of wetland elevation to changes in the rates of the following parameters that affect wetland elevation: deep subsidence, mineral inputs, primary production, decomposition of refractory and labile organic matter, and ESLR. Each parameter was varied plus and minus 50% of the original initialization value, and the model was allowed to run for 10 years. Sensitivity range was defined as: (final relative elevation after 10 years when parameter value = (initial parameter value * 0.5)) − (final relative elevation after 10 years when parameter value = (initial parameter value * 1.5)). Higher sensitivity ranges indicate greater sensitivity to a given parameter.

Sea Level Rise Scenarios. To simulate the effect of rising eustatic sea levels at the two sites, we varied the ESLR forcing function to simulate two scenarios; a rise of 0.15 cm year^{-1} to reflect no acceleration in current rates (hereafter referred to as the current conditions scenario), and a sea level rise of 48 cm by the year 2100 that reflects the central value reported by the Intergovernmental Panel on Climate Change (IPCC) for seven Atmospheric-Ocean General Circulation Models run under 35 different emission scenarios (hereafter referred to as the central value scenario) (Church et al. 2001). Although the central value of 48 cm is not necessarily the best possible estimate of future sea level rise trends, it is the same as an earlier IPCC best-guess rate reported by Wigley and Raper (1992). All simulations began in model year 1995 and were run for 100 simulated years.

The ESLR function plus the deep subsidence forcing function represents RSLR in the wetland and it was difficult to assign a value for the deep subsidence parameter since there are a wide range of values reported in the literature (Table 4). To choose a deep subsidence rate for each marsh we considered the proximity of the tidal gauge to the marsh sites (since deep subsidence values are derived from tidal gauge records); the length of the tidal gauge record (the longer the better, some records spanned six or seven decades while others spanned less than one); and the frequency of the reported value (i.e., if several gauges recorded deep subsidence values that were within the same range, and one or two reports appeared to be outliers, we would lean towards the former set of values). Given these considerations, we assigned rates of 1.18 cm year^{-1} for Bayou Chitigue and 0.7 cm year^{-1} for Old Oyster Bayou as baseline deep subsidence functions.

Deep Subsidence and Pulsing Event Scenarios. The ESLR scenario simulations described above re-

TABLE 5. Comparison of 8-year records of vertical accretion and elevation change with current estimates of relative sea level rise (RSLR).[1]

Marsh	Vertical Accretion	Elevation Change	RSLR[2]	Elevation Deficit[3]	Shallow Subsistence	Revised RSLR[4]
Bayou Chitigue	2.26 (0.09)	0.22 (0.06)	1.33	1.1	2.04 (0.1)	3.37
Old Oyster Bayou	0.48 (0.09)	0.36 (0.08)	0.85	0.49	none	0.85

[1] Units are cm yr^{-1}. Values for vertical accretion, elevation change, and shallow subsidence are means with standard error in parentheses.

[2] Relative sea level rise (RSLR) is calculated as deep subsidence (Table 1) plus a eustatic sea level rise of 0.15 cm yr^{-1}.

[3] Elevation deficit is calculated as relative sea level rise minus elevation change.

[4] Revised relative sea level rise is calculated by adding shallow subsidence to relative sea level rise.

vealed that the marsh at Old Oyster Bayou was not keeping pace with current rates of sea level rise. These results contradict long-term observations that the Old Oyster Bayou Marsh is stable (Britch and Dunbar 1996). We hypothesized that this apparent contradiction could be due to either overestimating the rates of deep subsidence (as a model forcing function) or underestimating the contribution of sediment pulsing events towards maintaining elevation. To examine the relative effect of deep subsidence on wetland elevation over the next 100 years at the Old Oyster Bayou Marsh, we held the ESLR constant at 0.15 cm $year^{-1}$, and varied the deep subsidence component of RSLR using the estimates shown in Table 1.

To simulate a pulsing event we referred to Hurricane Andrew, which delivered a 2 cm thick sediment pulse to Old Oyster Bayou in 1992 (Cahoon et al. 1995). Given a bulk density of 0.87 g cm^{-3} and a mineral fraction of 95% for this sediment layer (derived from core samples taken as part of this study), we calculated that the storm deposited approximately 16,500 g m^{-2} of mineral sediment to the marsh. From 1886 to 1998, there were nine storms with wind over 161 kilometers $hour^{-1}$ (100 mph) that affected Old Oyster Bayou (a return rate of once every 12 years) (Doyle and Girod 1997). For Old Oyster Bayou, we simulated a once-per-12-year pulse of 16,500 g m^{-2} mineral sediment to the wetland for four different RSLR scenarios: ESLR = current conditions, deep subsidence = 0.35 cm yr^{-1}; ESLR = current conditions, deep subsidence = 0.7 cm yr^{-1}; ESLR = central value, deep subsidence = 0.35 cm yr^{-1}; and ESLR = central value, deep subsidence = 0.7 cm yr^{-1} to determine if we could simulate a stable marsh.

Results and Discussion

FIELD STUDIES

As reported by Cahoon et al. (1999) and Kemp et al. (1999), the accretionary dynamics and geotechnical aspects of the marshes at Bayou Chitigue and Old Oyster Bayou differed significantly. During this eight-year period of field observations, vertical accretion at Bayou Chitigue was high (2.26 (0.09) cm yr^{-1}) (Fig. 3a) most likely because the marsh exists at the lower end of the tidal prism and is flooded 80% of the time (Cahoon et al. 1995), resulting in frequent opportunities for sediment deposition. Vertical accretion was 0.48 (0.09) cm yr^{-1} at Old Oyster Bayou (Fig. 3b), where the saltmarsh is situated 10 cm higher and is flooded only 20% of the time. Despite the large difference in vertical accretion, there was no significant difference ($p = 0.17$) in elevation change between the two marshes.

The deteriorating marsh at Bayou Chitigue gained only 0.22 (0.06) cm yr^{-1} of elevation as a result of 2.04 (0.1) cm yr^{-1} of shallow subsidence caused by the slow rate of consolidation of the chronically flooded soils at this site (Kemp et al. 1999). This rate of elevation gain at Bayou Chitigue lagged behind RSLR by more than 1.1 cm yr^{-1}. The current rate of RSLR used to calculate the elevation deficit was estimated from tide gauge data and therefore does not include the large amount of shallow subsidence measured at this site (Cahoon et al. 1999). When the amount of shallow subsidence is added to RSLR, the new estimate of RSLR is greater than 3.0 cm yr^{-1} (Table 5), which explains why the site is disintegrating so rapidly. Even a 3.0 cm thick episodic sediment deposit by Hurricane Andrew in 1992 could not increase elevation (Fig. 3a). The storm apparently caused a decrease in elevation of the weak substrate (Cahoon et al. 1995). Given the high rate of submergence presently occurring at this marsh and the ineffectiveness of episodic storm deposits to slow the rate of marsh deterioration, this short-term field record of elevation change strongly suggests that the Bayou Chitigue marsh will continue to fall below sea level and eventually disintegrate.

The rate of elevation gain at the Old Oyster Bayou marsh was 0.36 (0.08) cm yr^{-1}, which was not statistically different from the rate of vertical accretion for this site (i.e., there was no significant shallow subsidence). At Old Oyster Bayou, marsh elevation gain lagged behind RSLR by 0.49 cm yr^{-1} (Table 5), suggesting that this marsh is vulnerable to submergence. The short-term field record may

TABLE 6. Calibration checkpoints for all sites. For additional calibration checks see Figs. 2 and 3. Observed values are reported as mean ± standard error.

Site	Parameter	Observed[1]	Simulated
Bayou Chitigue	Aboveground NPP	798 ± 288 g m^2 yr^{-1}	526 g m^2 yr^{-1}
	Accretion	2.26 ± 0.09 cm yr^{-1}	1.88 cm yr^{-1}
	Surface Elevation Change	0.22 ± 0.06 cm yr^{-1}	0.28 cm yr^{-1}
Old Oyster Bayou	Aboveground NPP	987 ± 283 g m^2 yr^{-1}	1055 g m^2 yr^{-1}
	Accretion	0.48 ± 0.09 cm yr^{-1}	0.46 cm yr^{-1}
	Surface Elevation Change	0.36 ± 0.08 cm yr^{-1}	0.38 cm yr^{-1}

[1] See Table 1 for the sources of these data.

be misleading, however. There was no significant shallow subsidence at this stable marsh (0.12 cm yr^{-1}). A 2.0 cm sediment deposit by Hurricane Andrew resulted directly in a 2.0 cm elevation gain, and there was virtually no sediment compaction for the year following this storm deposit (Fig. 3b). Given the position of this marsh at 10 cm above mean sea level, the ability of this marsh to survive could be strongly influenced by the frequency of occurrence of major depositional events and by the potential for additional deposition as elevation decreases. The long-term survival of this marsh is difficult to predict from this short-term field record, so it is explored further using model simulations.

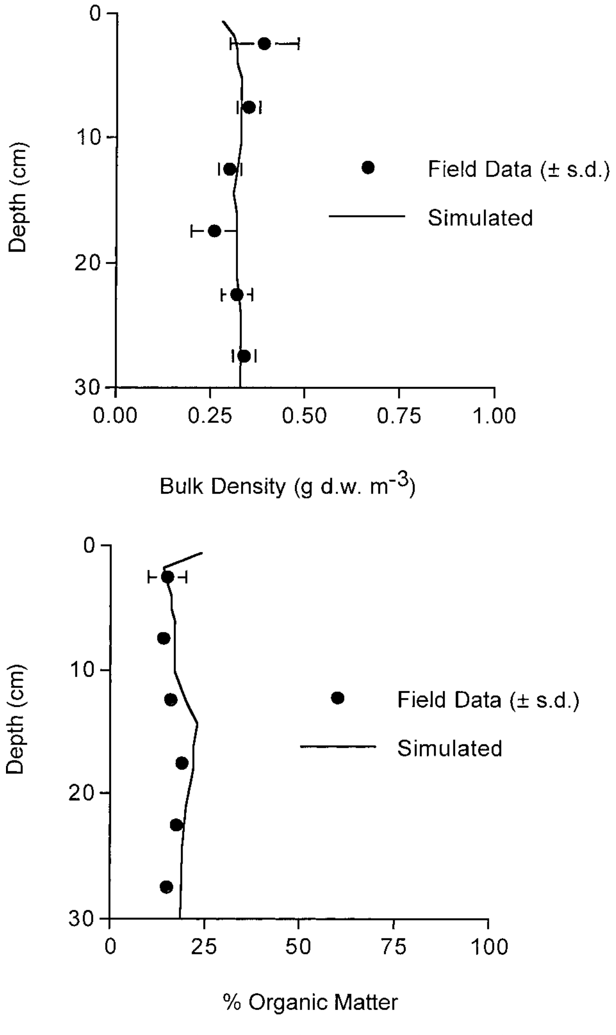


Fig. 4. Bayou Chitigue sediment profile with depth. Field measurements are shown as dots with standard deviation bars. Solid lines represent simulated results.

MODEL CALIBRATION

Simulated aboveground production fell within one standard error of values measured in the field (Table 6). For both sites, simulated bulk density and percent organic matter fell within one standard deviation of observed values (Figs. 4 and 5). There was some deviation between actual and simulated values at the top of the sediment column for both sites. Specifically, simulated bulk density was lower than observed values, and, to a lesser extent, simulated organic matter was higher than observed values. These discrepancies were most likely caused by a pulse of mineral matter from Hurricane Andrew in 1992 that was not simulated as part of the calibration. As an additional calibration check, observed and simulated surface elevation change and accretion rates were also in close agreement for both sites (Table 6).

SENSITIVITY ANALYSES

For both sites, the analyses revealed that simulated wetland elevation was most sensitive to the rate of deep subsidence and mineral inputs. It is important to note that the uncertainty surrounding estimates for deep subsidence in the Terrebonne Parish region varies by an order of magnitude (Table 1). Most estimates of RSLR, and deep subsidence, are made from the analysis of long-term tidal gauge records, and for both Bayou Chitigue and Old Oyster Bayou wetlands, there were no gauges in the immediate vicinity. Instead, estimates of RSLR were taken from either the nearest gauges or derived from basin-wide estimates of deep subsidence. Other factors, such as gauge placement and the time span of the gauge record,

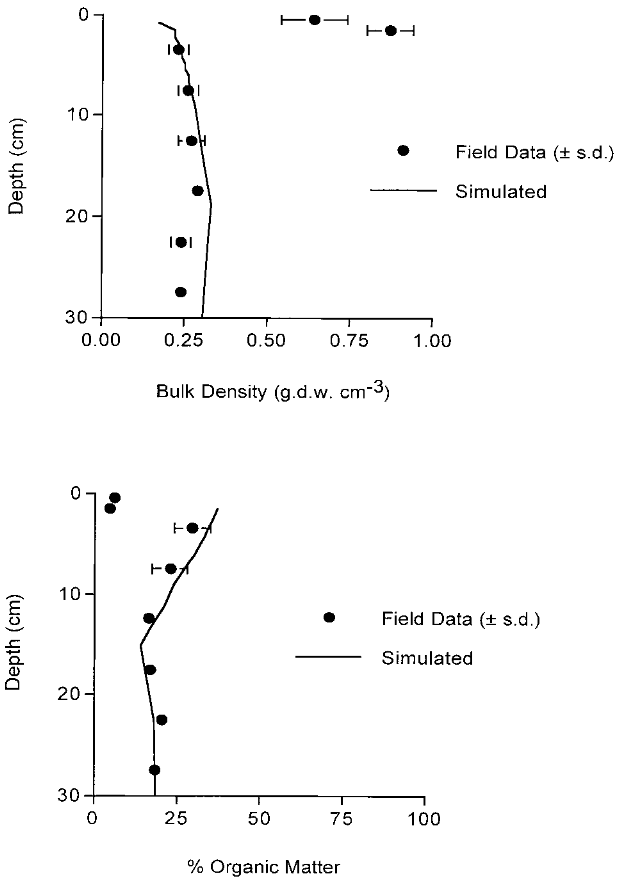


Fig. 5. Old Oyster Bayou sediment profile with depth. Field measurements are shown as dots with standard deviation bars. Solid lines represent simulated results.

also affect the uncertainty surrounding the estimates of RSLR and are discussed in detail by Turner (1991). Measurements derived from SETs, and models, can give some indication of wetland sustainability; however, SETs do not measure deep subsidence, and, in this model, deep subsidence is a forcing function.

The uncertainties surrounding estimated rates of belowground productivity in *Spartina alterniflora* salt marshes were discussed earlier and this analysis revealed that wetland elevation was moderately sensitive to this parameter. This sensitivity suggests that further empirical studies linking belowground production to elevation (or even further studies simply measuring belowground productivity) may be critical for predicting the sustainability of coastal marshes given rising sea levels.

These analyses revealed that wetland elevation was relatively insensitive to the parameters that control the rates of organic matter decomposition (Table 7). These results are in general agreement with those of other researchers (Callaway et al. 1996; Day et al. 1999) whose models have shown relatively low sensitivity to the same parameters.

TABLE 7. Sensitivity of wetland elevation to environmental model parameters. Sensitivity analyses were carried out using the initial value for each parameter, the initial value plus 50%, and the initial value minus 50%. Each analysis was run for 10 years. Sensitivity range is defined as: (final relative elevation after 10 years when parameter value = (initial parameter value*0.5)) − (final relative elevation after 10 years when parameter value = (initial parameter value*1.5)). BC = Bayou Chitigue; OOB = Old Oyster Bayou.

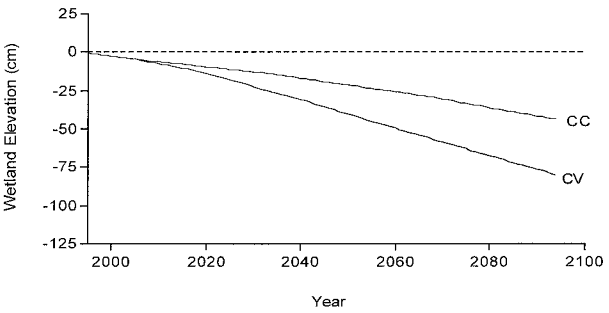
		Sensitivity Range (cm)	
Parameter	Description	BC	OOB
surate	deep subsidence rate	11.71	5.67
max_min_in	maximum mineral input	6.17	4.50
maxnet	primary production rate	5.79	5.18
krefr	decomposition rate of refractory organic matter	1.81	2.05
eslr_c	current rate of ESLR	1.50	1.13
klab	decomposition rate of labile organic matter	0.60	0.10

ESLR SCENARIOS

For Bayou Chitigue, the simulations revealed that wetland elevation remained below mean sea level (MSL) for both sea level rise scenarios for the entire 100-year simulation (Fig. 6a). Under the current conditions scenario, wetland elevation relative to mean sea level decreased to −44.0 cm after 100 years (Table 8). Under the central value scenario, final wetland elevation decreased to −80.0 cm below MSL after 100 years (Table 8). This result is not unexpected given that estimated deep subsidence is high at this site and that the initial wetland elevation was set to 0 cm MSL (even using the lower estimate of deep subsidence of 0.85 cm year^{-1} reported in Table 1, simulated wetland elevation remained below sea level for both sea level rise scenarios). Since mineral inputs are maximized as elevation decreases, and mineral inputs approach the maximum as wetland elevation approaches 0 cm above MSL (Callaway et al. 1996), there was no potential for significant increases in mineral inputs to reverse the trend towards decreasing elevation (since elevation was already at 0 cm above MSL). A positive feedback is also in operation: as relative elevation decreases, simulated primary production decreases, which in turn contributes to further decreases in wetland elevation. These simulations confirm field measurements and observations.

At the Old Oyster Bayou marsh, simulated wetland elevation also decreased for both sea level rise scenarios (Fig. 6b), although not as dramatically as at Bayou Chitigue. Given the current conditions scenario, Old Oyster Bayou elevation fell below

a. Bayou Chitigue



b. Old Oyster Bayou

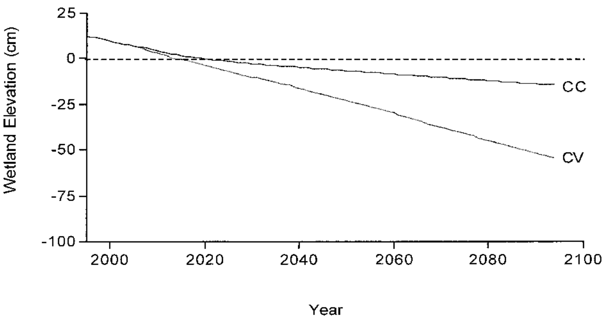


Fig. 6. Bayou Chitigue (a) and Old Oyster Bayou (b) wetland elevation relative to sea level rise for two Intergovernmental Panel on Climate Change eustatic sea level rise scenarios: (1) CC = Current Conditions, 15 cm eustatic sea level rise in the next 100 years and (2) CV = Central Value, 48 cm eustatic sea level rise by the year 2100. Wetland elevation is plotted relative to sea level, therefore sea level (the dashed line) appears level.

MSL after 25 years and declined to −14.8 cm below MSL after 100 years. Under the central value scenario, elevation fell below MSL in 18 years and declined to −54.5 cm below MSL after 100 years (Table 8). Both the field measurements and the simulated current conditions scenario suggest that wetland elevation is declining in relation to sea level at Old Oyster Bayou, although the simulated decline over 100 years, 0.27 cm yr^{-1}, is approximately half the current rate of decline measured in the field (0.49 cm yr^{-1}) (Table 5). The simulated rate is lower because the initial elevation at this site is relatively high (10 cm above MSL) and, since mineral inputs are maximized as wetland elevation decreases, there is a potential for additional mineral inputs as wetland elevation decreases relative to sea level. In the model, annual mineral inputs increase from 1,100 g m^{-2} yr^{-1} at time zero (similar to actual current inputs at the site) to 2,100 g m^{-2} yr^{-1} after 100 years. In effect, the model takes into account this elevation/mineral-input feedback, while estimates made from field measurements do not.

Both the field and simulated results run contrary to other long-term observations that suggest that the Old Oyster Bayou marsh is in long-term equilibrium (at least 50 years) with sea level (Britch and Dunbar 1996). We offer two possible explanations for why the field and modeling results indicate that the rate of sediment accumulation in the marsh is not keeping pace with the current rate of RSLR. First, given the known model sensitivity to the rates of deep subsidence (Table 7), and that the estimates for deep subsidence in the region vary by an order of magnitude (Table 1), it is possible that the deep subsidence forcing function rate used for these simulations (0.7 cm yr^{-1}) is too high. Second, simulations do not include occasional pulsing events, such as hurricanes, that can contribute significant, if not critical, amounts of sediment to the marsh surface (Day et al. 1995). In the following sections we show the results of a series of simulations in which we vary the rates of deep subsidence and add a sediment pulsing function to the model to determine if either can reasonably propagate stability at the Old Oyster Bayou site given various sea level rise scenarios.

TABLE 8. Final wetland elevation, relative to mean sea level, after 100 years (starting in 1995) given two Intergovernmental Panel on Climate Change (IPCC) eustatic sea level rise scenarios.

	Final Wetland Elevation After 100 Years	
IPCC Eustatic Sea Level Rise Scenarios	Bayou Chitigue	Old Oyster Bayou
a. Current Conditions (15 cm in the next 100 years)	−44.0 cm	−14.8 cm
b. Central Value (48 cm by the year 2100)	−80.0 cm	−54.5 cm

Deep Subsidence and Pulsing Events

Varying the deep subsidence forcing function over the range of values shown in Table 1 (and holding ESLR constant at 0.15 cm yr^{-1}) revealed that wetland elevation at Old Oyster Bayou was sustainable only under the most conservative estimates of deep subsidence for the region (0.35 cm yr^{-1}) (Fig. 7). The episodic pulsing simulations revealed that wetland elevation would remain above MSL over the next 100 years given three scenarios (ESLR = current conditions, deep subsidence = 0.35 cm yr^{-1}; ESLR = current conditions, deep subsidence = 0.7 cm yr^{-1}; and ESLR = central value, deep subsidence = 0.35 cm yr^{-1}), but not a fourth scenario (ESLR = central value, deep subsidence = 0.7 cm yr^{-1}; Fig. 8).

Under the current conditions ESLR scenario, wetland stability at Old Oyster Bayou could be simulated by either dramatically reducing the rate of deep subsidence (to 0.35 cm yr^{-1}) or by adding a

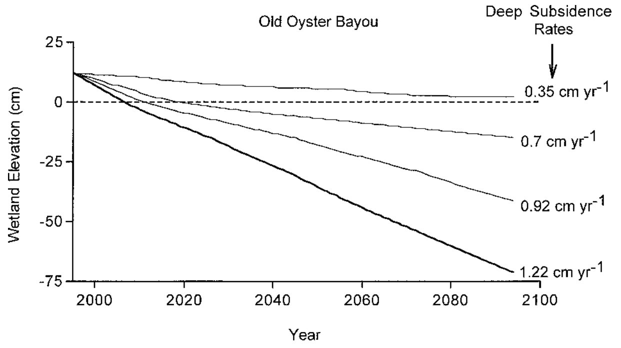


Fig. 7. Simulated changes in Old Oyster Bayou wetland elevation, relative to sea level (dashed line), based on four published rates of deep subsidence (see Table 1 for sources). Eustatic sea level rise is held constant at the "current conditions" rate of 15 cm in the next 100 years.

simulated sediment pulse. Which scenario is more likely?

It is generally agreed that the rates of deep subsidence in the Mississippi River delta region are high, commonly exceeding 1.0 cm yr^{-1} (Penland et al. 1988). Certainly a rate of 0.7 cm yr^{-1} would not be considered excessive, while a rate of 0.35 cm yr^{-1} would be considered low (see Table 1). It is unlikely that an overestimate of the simulated rate of deep subsidence (0.7 cm yr^{-1}) is responsible for the simulated elevation deficit at Old Oyster Bayou.

Several pieces of evidence suggest that pulsing events may play an important role in maintaining elevation at the Old Oyster Bayou marsh. Studies have shown that this area of the coast is subject to frequent hurricane and tropical storm strikes that could deposit large amounts of sediments on the marsh surface. As discussed previously, Doyle and Girod (1997) calculated a return frequency of 12 years for storms with winds over 161 km h^{-1}. Muller and Stone (2001) found that, for the period 1901 through 2000, the coastline near Old Oyster Bayou was struck by seven category 3–5 hurricanes, three category 1–2 hurricanes and twenty-five tropical storms.

A comparison of long- and short-term rates of accretion (as measured by ^{137}Cs and feldspar marker horizons, respectively) at the marsh (Table 1) provides some evidence of past sediment pulsing events. Current rates of accretion, as measured by feldspar horizon markers, average 0.44 cm yr^{-1}, but the rates of accretion as measured by the ^{137}Cs technique averages 0.71 cm yr^{-1}. Normally, short-term measurements of accretion yield estimates of accretion rates that are higher than estimates derived from longer term methods because short-term methods fail to integrate long-term process such as decomposition and sediment compaction that tend to reduce the apparent accretion. If estimates of accretion are higher from long-term records than short-term records, as is the case here, one possible explanation is that the longer term record integrates infrequent sediment pulses that the short-term record from feldspar marker horizons may not have captured.

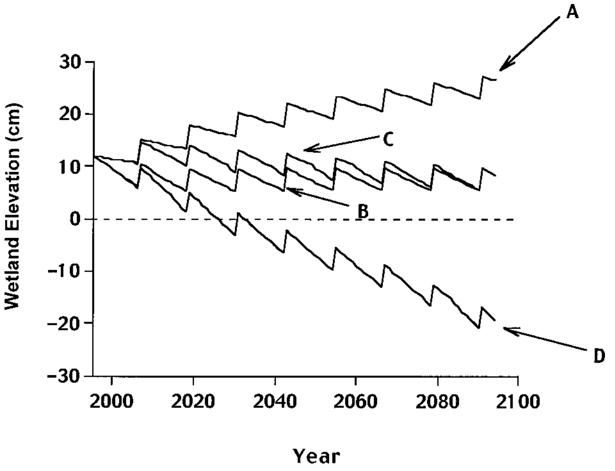


Fig. 8. Simulated wetland elevation at Old Oyster Bayou, relative sea level (dashed line), given a 16,500 g m^{-2} pulse of mineral sediments every 12 years, and four different relative sea level rise scenarios: (A) eustatic sea level rise = 15 cm over the next 100 years and deep subsidence = 0.35 cm yr^{-1}; (B) eustatic sea level rise = 15 cm over 100 years and deep subsidence = 0.7 cm yr^{-1}; (C) eustatic sea level rise = 48 cm over 100 years and deep subsidence = 0.35 cm yr^{-1}; and (D) eustatic sea level rise = 48 cm over 100 years and deep subsidence = 0.7 cm yr^{-1}.

Pollen analysis and visual examination of cores collected from the Atchafalaya Marsh near Old Oyster Bayou revealed three layers in the upper 25 centimeters (dating back approximately 34 years) corresponding chronologically with Hurricanes Andrew (1992), Carmen (1974) and Hilda (1964) (Zhou 1998).

Conclusions

The use of computer simulations allows us to easily examine changes in wetland elevation relative to sea level over a range of subsidence and sea level rise scenarios and extend the conclusions drawn from field observations. Both field measurements and simulations are dependent upon the forcing functions ESLR and deep subsidence to make predictions concerning short- and long-term sustainability. Our field and modeling results suggest that, given the most likely set of forcing functions (ESLR = 48 cm in the next 100 years, deep subsidence = 1.18 cm yr^{-1} for Bayou Chitigue and 0.7 cm yr^{-1} for Old Oyster Bayou), neither site can maintain its elevation over the next 100 years (Figs. 3 and 6). For the Old Oyster Bayou site, even a pulse of 16,500 g m^{-2} of sediment every twelve years was not enough to maintain elevation under increasing rates of sea level rise (Fig. 8), although both field and modeling results suggested that pulsing events are critical for maintaining elevation under current sea level rise rates.

There will always be a large amount of uncertainty when it comes to predicting the fate of coastal salt marshes given various global warming scenarios. Estimated rates of both deep subsidence and sea level rise can vary by an order of magnitude (Turner 1991; Gornitz 1995). By definition, the frequency and magnitude of sediment pulsing events are difficult to predict and quantify and may change as climate changes. Field data concerning critical processes that contribute to marsh building and degradation, such as belowground production, absolute maximum rates of mineral inputs, and long-term decomposition, are scarce. Despite this, we believe that coordinated field and modeling programs such as this provide the best available tools for predicting future wetland sustainability given rising sea levels. The simultaneous use of surface elevation tables and accretion markers not only give some indication for the potential for submergence, but they provide the data required to initialize, calibrate, and validate the models used to make longer term predictions.

ACKNOWLEDGMENTS

This work was funded by the USGS Global Climate Research Program. We wish to thank Darren Johnson who assisted with the statistical analysis, Jim Lynch, who developed the site map and provided other critical data. We also thank Tammy Charron, Sacha Maxwell, and Tammy Hershberger, who provided editorial comments. We are indebted to John Callaway, Gail Chmura, Tom Doyle, and one anonymous reviewer for their careful and insightful suggestions that substantially improved the manuscript.

LITERATURE CITED

ALLEN, J. R. S. 1990. The formation of coastal peat marshes under an upward tendency of relative sea level. *Journal of the Geological Society of London* 147:743–747.

BOESCH, D. F., M. N. JOSSELYN, A. J. MEHTA, J. T. MORRIS, W. K. NUTTLE, C. A. SIMENSTAD, AND D. J. SWIFT. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. *Journal of Coastal Research* Special Issue 20: 1–103.

BOESCH, D. F., D. LEVIN, D. NUMMEDAL, AND K. BOWLES. 1983. Subsidence in Coastal Louisiana: Causes, Rates, and Effects on Wetlands. FWS/OBS-83/26. U.S. Fish and Wildlife Service, Division of Biological Services, Washington D.C.

BRITCH, L. D. AND J. B. DUNBAR. 1996. Land Loss in Coastal Louisiana. A Series of Seven Color Maps of Coastal Land Loss. Technical Report GL-90-2, Maps 1–7. U.S. Army Corps of Engineers, Vicksburg, Mississippi and U.S. Army Corps of Engineers District, New Orleans, Louisiana.

CAHOON, D. R., J. W. DAY, JR., AND D. J. REED. 1999. The influence of surface and shallow subsurface soil processes on wetland elevation: A synthesis. *Current Topics in Wetland Biogeochemistry* 3:72–88.

CAHOON, D. R., J. W. DAY, JR., D. J. REED, AND R. S. YOUNG. 1998. Global climate change and sea level rise: Estimating the potential for submergence of coastal wetlands, p. 19–32. *In* G. R. Guntenspergen and B. A. Vairin (eds.). Vulnerability of Coastal Wetlands in the Southeastern United States: Climate Change Research Results, 1992–1997. Biological science report USGS/BRD/BSR—1998–2002. Biological Resources Division, U.S. Geological Survey, Reston, Virginia.

CAHOON, D. R., J. C. LYNCH, AND R. M. KNAUS. 1996. Improved cryogenic coring device for sampling wetland soils. *Journal of Sedimentary Research* 66:1025–1027.

CAHOON, D. R., D. J. REED, AND J. W. DAY. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* 128:1–9.

CALLAWAY, J. C., J. A. NYMAN, AND R. D. DELAUNE. 1996. Sediment accretion in coastal wetlands: A review and a simulation model of processes. *Current Topics in Wetland Biogeochemistry* 2: 2–23.

CHMURA, G. L, R. COSTANZA, AND E. C. KOSTERS. 1992. Modeling coastal marsh stability in response to sea level rise: A case study in coastal Louisiana, USA. *Ecological Modeling* 64:47–64.

CHURCH, J. A., J. M. GREGORY, P. HUYBRECHTS, M. KUHN, K. LAMBECK, M. T. NHUAN, D. QIN, AND P. L. WOODWORTH. 2001. Changes in sea level, p. 639–693. *In* J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.). Climate Change 2001: The Scientific Basis. Third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, U.K.

DAY, J. W., D. PONT, P. HENSEL, AND C. IBANEZ. 1995. Impacts of sea level rise on deltas in the Gulf of Mexico and the Mediterranean: The importance of pulsing events to sustainability. *Estuaries* 18:636–647.

DAY, J. W., J. RYBCZYK, F. SCARTON, A. RISMONDO, D. ARE, AND G. CECCONI. 1999. Soil accretionary dynamics, sea level rise and the survival of wetlands in the Venice Lagoon: A field and modeling approach. *Estuarine, Coastal and Shelf Science* 49:607–628.

DOYLE, T. W. AND G. F. GIROD. 1997. The frequency and intensity of Atlantic hurricanes and their influence on the structure of south Florida mangrove communities, p. 109–120. *In* H. F. Diaz and R. S. Pulwarty (eds.). Hurricanes: Climate and Socioeconomic Impacts. Springer-Verlag, Berlin, Germany.

FRENCH, J. R. 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea level rise, North Norfolk, United Kingdom. *Earth Surface Processes and Landforms* 18:63–81.

GALLAGHER, J. AND F. G. PLUMLEY. 1979. Underground biomass profiles and productivity in Atlantic coastal marshes. *American Journal of Botany* 66:156–161.

GORNITZ, V. 1995. Sea level rise: A review of recent past and near-future trends. *Earth Surface Processes and Landforms* 20:7–20.

GROSS, M. F., M. A. HARDISKY, AND P. L. WOLF. 1991. Relationship between aboveground and belowground biomss in *Spartina alterniflora* (smooth cordgrass). *Estuaries* 14:180–191.

KEMP, G. P., J. W. DAY, JR., D. J. REED, D. R. CAHOON, AND M. WANG. 1999. Sedimentation, consolidation and surface elevation change in two salt marshes of the Mississippi River Deltaic Plain: Geotechnical aspects of wetland loss, p. 15–34. *In* L. P. Rozas, J. A. Nyman, C. E. Proffitt, N. N. Rabalais, D. J. Reed, and R. E. Turner (eds.). Recent Research in Coastal Louisiana: Natural System Function and Response to Human Influence. Louisiana Sea Grant College Program, Baton Rouge, Louisiana.

KUHN, N. L. AND I. A. MENDELSSOHN. 1999. Halophyte sustainability and sea level rise: Mechanisms of impact and possible solutions, p. 113–26. *In* H. Lieth (ed.). Halophyte Uses in

Different Climates I. Backhuys Publishers, Leiden, The Netherlands.

Lessmann, J. M., I. A. Mendelssohn, M. W. Hester, and K. L. McKee. 1997. Population variation in growth response to flooding of three marsh grasses. *Ecological Engineering* 8:31–47.

McKee, B. A. 1994. Patterns and rates of sedimentation: Radionuclides as particle tracers, p. 1–16. *In* H. H. Roberts (Project Coordinator). Critical Physical Processes of Wetland Loss: Final Report. U.S. Geological Survey, Reston, Virginia.

Mitsch, W. J. and B. C. Reeder. 1991. Modeling nutrient retention of a freshwater coastal wetland: Estimating the roles of primary productivity, sedimentation, resuspension and hydrology. *Ecological Modeling* 54:151–187.

Morris, J. T. and W. B. Bowden. 1986. A mechanistic, numerical model of sedimentation, mineralization and decomposition for marsh sediments. *Soil Science Society of America Journal* 50: 996–1005.

Muller, R. A. and G. W. Stone. 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast U.S. coast. *Journal of Coastal Research* 17: 949–956.

Murray, S. P., N. D. Walker, and C. E. Adams, Jr. 1993. Impacts of winter storms on sediment transport within the Terrebonne Bay marsh complex, p. 56–70. *In* S. Laska and A. Puffer (eds.). Coastlines of the Gulf of Mexico. American Society of Civil Engineers, New York.

Penland, S. and K. E. Ramsey. 1990. Relative sea level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research* 6:323–342.

Penland, S., K. E. Ramsey, R. A. McBride, J. T. Mestayer, and K. A. Westphal. 1988. Relative Sea Level Rise and Delta-plain Development in the Terrebonne Parish Region. Coastal geology technical report. Louisiana Geological Survey, Baton Rouge, Louisiana.

Richmond, B., S. Peterson, and P. Vescuso. 1987. An Academic User's Guide to STELLA. High Performance Systems, Lyme, New Hampshire.

Rybczyk, J. M., J. C. Callaway, and J. W. Day. 1998. A relative elevation model (REM) for a subsiding coastal forested wetland receiving wastewater effluent. *Ecological Modeling* 112:23–44.

Schubauer, J. and C. Hopkinson. 1984. Above- and belowground emergent macrophyte production and turnover in coastal marsh ecosystem, Georgia. *Limnology and Oceanography* 29:1052–1065.

Turner, R. E. 1991. Tide gauge records, water level rise, and subsidence in the northern Gulf of Mexico. *Estuaries* 14:139–147.

Wigley, T. M. L. and S. C. B. Raper. 1992. Implications for climate and sea level of revised IPCC emission scenarios. *Nature* 330:293–300.

Zhou, X. 1998. A 4000 year pollen record of vegetation changes, sea level rise, and hurricane disturbance in the Atchafalaya Marsh of southern Louisiana. M.S. Thesis, Louisiana State University, Baton Rouge, Louisiana.

Received for consideration, November 13, 2000
Accepted for publication, March 11, 2002