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Soil Accretionary Dynamics, Sea-Level Rise and the Survival of Wetlands in Venice Lagoon: A Field and Modelling Approach

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Over the past century, Venice Lagoon (Italy) has experienced a high rate of wetland loss. To gain an understanding of the factors leading to this loss, from March 1993 until May 1996 the soil accretionary dynamics of these wetlands were studied. Vertical accretion, short term sedimentation, soil vertical elevation change and horizontal shoreline change were measured at several sites with varying sediment availability and wave energy. Short term sedimentation averaged 3–7 g dry m^{-2} day^{-1} per site with a maximum of 76 g m^{-2} day^{-1}. The highest values were measured during strong pulsing events, such as storms and river floods, that mobilized and transported suspended sediments. Accretion ranged from 2–23 mm yr^{-1} and soil elevation change ranged from -32 to 13·8 mm yr^{-1}. The sites with highest accretion were near a river mouth and in an area where strong wave energy resuspended bottom sediments that were deposited on the marsh surface. A marsh created with dredged spoil had a high rate of elevation loss, probably due mainly to compaction. Shoreline retreat and expansion of tidal channels also occurred at several sites due to high wave energy and a greater tidal prism. The current rate of elevation gain at some sites was not sufficient to offset relative sea-level rise. The results suggest that reduction of wave energy and increasing sediment availability are needed to offset wetland loss in different areas of the lagoon. Using the data collected as part of this project, we developed a wetland elevation model designed to predict the effect of increasing rates of eustatic sea-level rise on wetland sustainability. The advantage of this model, in conjunction with measured short-term rates of soil elevation change, to determine sustainability is that the model integrates the effects of long term processes (e.g. compaction and decomposition) and takes into account feedback mechanisms that affect elevation. Specifically, changes in elevation can result in changes in allogenic sediment deposition, decomposition and autogenic primary production. Model results revealed that, given the Intergovernmental Panel on Climate Change (IPCC) ‘ best estimate ’ eustatic sea-level rise scenario of 48 cm in the next 100 years, only one site could maintain its elevation relative to sea level over the next century. Under the IPCC ‘ current conditions’ scenario of 15 cm in the next 100 years, four of seven sites remained stable. This work demonstrates that more accurate predictions of the future of coastal wetlands with rising sea level will be obtained with a combination of short-term measurements of accretion and soil elevation change and long-term modelling.

Keywords: sedimentation; Venice Lagoon; sea-level rise; modelling; IPCC

Introduction

Coastal wetlands exist in a dynamic equilibrium, in both horizontal and vertical planes, between forces which lead to their establishment and maintenance, and forces which lead to deterioration. In the vertical plane, of the most important processes currently affecting coastal wetlands is rising sea level. If marshes are to survive rising water levels, they must be able to accrete at a rate such that surface elevation gain is sufficient to offset the rate of water level rise (Cahoon *et al.*, 1995*b*). A number of studies have shown that coastal marshes are able to accrete at a rate equal to the historical rate of eustatic sea-level rise (1–2 mm yr^{-1}, Gornitz *et al.*, 1982) and survive for long periods of time (Redfield, 1972; McCaffrey & Thompson, 1980; Orson *et al.*, 1987).

It is likely, however, that the rate of sea-level rise will accelerate over the coming 100 years by 4–6 mm yr^{-1} (Raper *et al.*, 1996). In addition, subsidence has caused relative sea-level rise (RSLR) to be much greater than the eustatic rate in a number

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of coastal systems. For example, in the Mississippi delta, RSLR is 10–12 mm yr^{-1}, primarily due to regional subsidence (Penland & Ramsey, 1990) and for the Nile Delta, the rate of subsidence is as high as 5 mm yr^{-1} (Stanley, 1988). The rate of background geologic subsidence in Venice Lagoon during the 20th century is 1·2–1·5 mm yr^{-1} (Pirazzoli, 1987; Carbognin *et al.*, 1996) resulting in a RSLR between 2·4 and 3·0 mm yr^{-1} (Albani *et al.*, 1983; Rusconi *et al.*, 1993). Groundwater withdrawal in the Venice area from the 1940s to the late 1960s led to RSLR as high as 8 mm yr^{-1} (Sestini, 1996). Marshes, however, can survive such high rates of RSLR if sediment input and *in situ* organic soil formation are sufficient. In the Mississippi Delta, for example, tidal creek streamside levee marshes and those near sources of riverine sediments are able to accrete vertically at rates higher than RSLR while back marshes generally have accretion rates less than RSLR (Baumann *et al.*, 1984; Hatton *et al.*, 1983). In Venice Lagoon, however, practically all riverine sediment input has been stopped (Bendoricchio *et al.*, 1993) and there is a strong net loss of sediments from the lagoon (Bettinetti *et al.*, 1995).

To determine if wetlands are growing vertically at a rate sufficient to offset water level rise, measurements of soil vertical accretion alone are insufficient. Measurements must also be made of the rate of soil elevation change because shallow subsidence may occur in the upper soil profile. Shallow subsidence is defined as the difference between vertical accretion and net surface elevation change (Cahoon *et al.*, 1995*b*). It provides an estimate of the degree of consolidation and compaction in the upper soil column, primarily the root zone, and is differentiated from deep subsidence such as is measured by long term tide gauge records.

In the horizontal plane, high wave energy on exposed marsh shores can lead to shoreline retreat, enlargement of interior marsh ponds and, at times, scour of the marsh surface (Stevenson *et al.*, 1985; Pethick, 1992). An increased tidal prism due to increased water depths resulting from bottom scour or sea-level rise leads to the deepening and widening of tidal channels (Pethick, 1992, 1993). In Venice Lagoon, marsh retreat is occurring in a number of areas. By analysing maps, Cavazzoni and Gottardo (1983) calculated that between 1933 and 1970 the edge of exposed marshes in the south-eastern lagoon retreated at rates of 0·8–2·7 m yr^{-1}. The lagoon has deepened by up to 30 cm due both to RSLR and longer fetch resulting from marsh retreat. There has been an expansion of the tidal network over the past several decades due to an increasing tidal prism (Consorzio Venezia Nuova, 1993). This is a synergistic process because as the marsh disappears, both fetch and the mean depth of the lagoon increase further. Thus, Venice Lagoon marshes are being affected by rising water levels, lower sediment input and increasing hydrodynamic energy. The purpose of this project was to study the soil dynamics and geomorphic response of wetlands in Venice Lagoon to a combination of sea-level rise and human alterations of the lagoon and to predict the future of these marshes with accelerated sea-level rise. In order to do this, measurements were made of a number of vertical and horizontal soil accretionary processes affecting the wetlands of Venice Lagoon and a wetland elevation model was developed to predict their long-term survival.

The objectives of the field study were: (a) to measure short-term sedimentation, vertical accretion, soil elevation change and shoreline change on varying time scales in different wetlands of Venice Lagoon; (b) to compare rates of accretion and soil elevation change with relative sea-level rise (RSLR) to determine if current rates of vertical growth are sufficient to offset present and predicted future rates of RSLR; (c) to evaluate the impacts of different human alterations on wetland sustainability.

It was also recognized that the direct comparison of short-term rates of accretion and soil elevation change to rates of RSLR, in order to predict wetland sustainability, can be misleading. This is because short term field measurements of accretion and shallow subsidence of one to several years do not fully integrate long term processes, such as compaction and decomposition, that affect wetland elevation. Additionally, such direct comparisons do not take into account elevation feedback mechanisms on the processes themselves. Specifically, processes which change with elevation include allogenic sediment deposition (French, 1993), decomposition (Webster & Bedfield, 1986) and autogenic primary production (Randerson, 1979). Therefore an integrated wetland elevation model was used, which can be simulated for decades and incorporates elevation feed back mechanisms, for predicting long term wetland sustainability in the face of increased RSLR and for evaluating the outcome of various mineral management scenarios in the wetlands of the Venice Lagoon. The model is a modified version of previous wetland elevation models developed by Callaway *et al.* (1996); and Rybczyk *et al.* (1998).

Area description

The Lagoon of Venice, the largest Italian lagoon and one of the largest of the Mediterranean, is located in

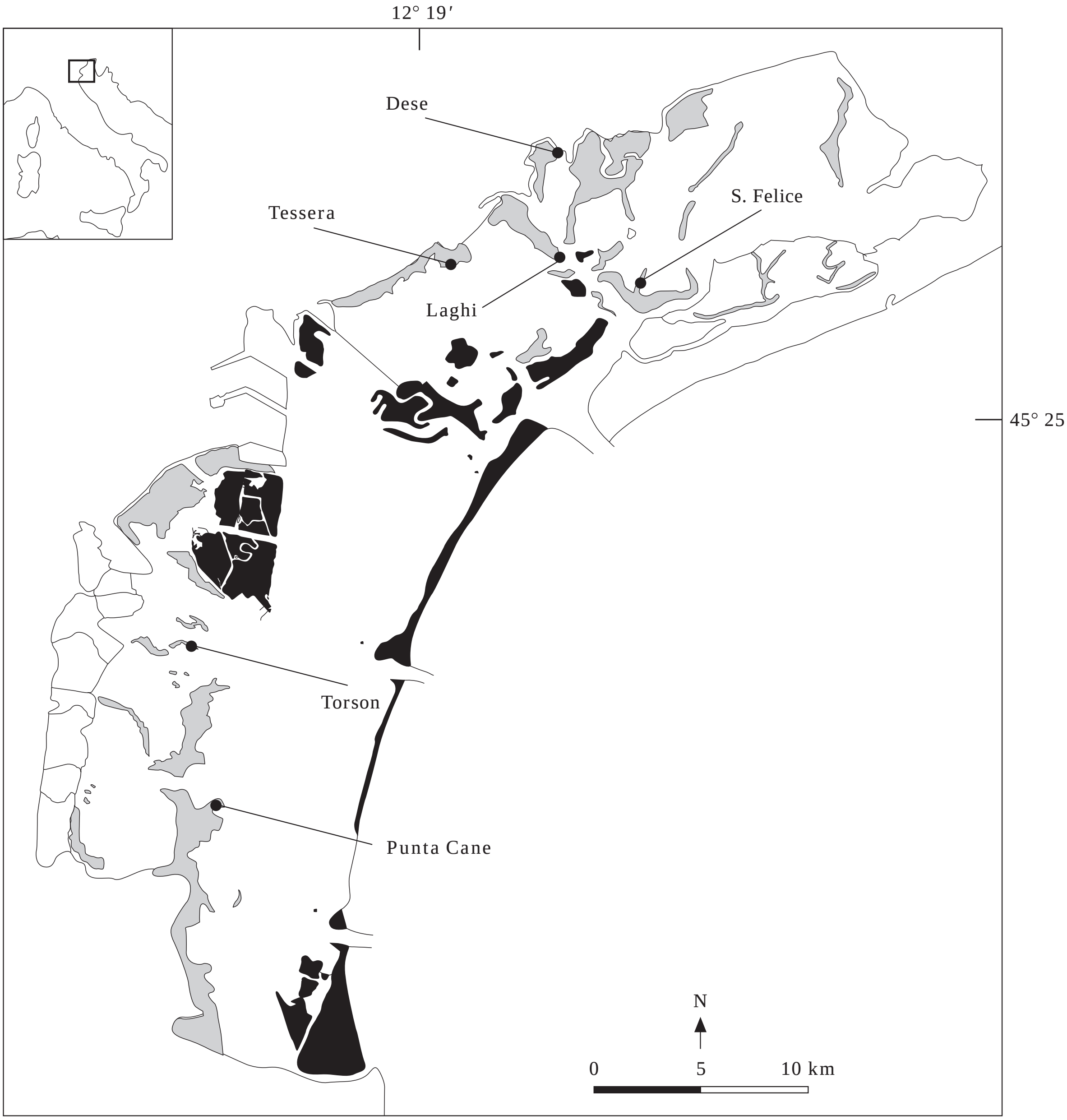


FIGURE 1. Map of Venice Lagoon showing the location of the study sites. Grey areas are marshes and black areas are islands within the lagoon. All sites were established in March 1993 with the exception of Torson and Punta Cane 2 (October 1993) and Tessera 2 and 4 (June 1994). See text for more detailed descriptions of the sites.

north-eastern Italy and has an area of approximately 550 km^2 (Figure 1). It exchanges water with the sea through three large inlets. Over the past five centuries, sediment dynamics of the lagoon have been greatly altered (Gatto & Carbognin, 1981). Three rivers, the Brenta, Sile, and Piave, which originally discharged into the lagoon, were diverted from the lagoon to the sea beginning in the 16th century. Presently, only a few small rivers (total discharge about 30 $m^3 s^{-1}$) discharge into the lagoon (Bendoricchio *et al*., 1993). Thus, riverine sediment input to the lagoon has been almost completely eliminated. The import of coarse marine sediments into the lagoon has been greatly reduced because of the construction of long jetties in the inlets at the end of the last century. Nowadays, there is a net export of about one million $m^3 yr^{-1}$ of sediments from the lagoon system (Bettinetti *et al*., 1995).

Most of the lagoon is occupied by a large central waterbody (about 370 km^2) and extensive intertidal salt marshes (about 40 km^2). The mean depth of the lagoon is 1·1 m and the tide range is 0·6–1 m, thus extensive tidal flats (about 50 km^2) are exposed at low tide. The subtidal areas are partially vegetated by macroalgae and seagrasses (such as *Zostera marina*, *Z. noltii* and *Cymodocea nodosa*). The dominant salt marsh species include *Limonium serotinum*, *Puccinellia palustris*, *Arthrocnemum fruticosum* and *Spartina maritima* (a listing of plant species of the lagoon is given by Gehu *et al.*, 1984). Species composition varies with elevation and Pignatti (1966) described vegetative associations correlated with elevation and other factors for Venice Lagoon wetlands. For the elevation range for our sites, Pignatti described four vegetation associations: a *Puccinellia–Arthrocnemum* association from 25 to 40 cm msl (above mean sea-level), a *Limonium–Puccinellia* association from 15–30 cm msl, a *Limonium–Spartina* association from 5–20 cm msl, and a *Salicornia* spp. association from 5–10 cm msl. The species associations at our sampling sites relative to elevation are similar to those described by Pignatti and are discussed in the sections on site description and soil elevation change and vegetative succession. The Venice Lagoon marshes are important in Europe due to their aerial extent, high productivity, and habitat value (Dijkema, 1984). Salt marsh area in the lagoon, has fallen from about 12 000 ha at the beginning of the century to about 4000 ha at present due to reclamation, erosion, pollution, and natural and human-induced subsidence (Favero, 1992; Runca *et al.*, 1993).

The marshes of Venice Lagoon occur in a highly variable environment with respect to salinity, sediment availability and hydrodynamic forces. In order to determine the effects of this variability on accretion and erosion processes, we selected sites in a number of representative marsh areas of the lagoon and stations were established in each of these in 1993 and 1994 (Figure 1). The elevation of the sites was determined using DGPS technology with an accuracy of ± 3 cm.

Site descriptions

San Felice. This salt marsh is located near the Lido inlet. Before the construction of jetties, this marsh is likely to have received inputs of coarser sediments from the near-shore Adriatic Sea (Albani *et al.*, 1983). Salt marshes in this area currently exist mainly as relatively narrow fringes along tidal creeks while interior zones between creeks are shallow ponds, which formed over the last several decades due to the disappearance of interior marsh. The study area is located between a tidal creek and a shallow pond. Sites were set up in each of two vegetation zones, a higher *A. fruticosum–L. serotinum–P. palustris* dominated marsh nearer the tidal creek (S. Felice 1, elevation 0·35 m msl) and a lower marsh dominated by *S. maritima* about 20 cm in height with a much lesser occurrence of *L. serotinum* (S. Felice 2, evaluation 0·29 m msl). Although the marshes at this site are relatively high, the soils have a high clay content and do not drain well.

Isola dei Laghi. This salt marsh is intermediate between the mouth of the Dese River and San Felice, and probably receives sediments from both the sea and river. Wetland vegetation is dominated by *Juncus maritimus*, with much lower occurrence of *S. maritima* and *L. serotinum*. A site was established in the marsh adjacent to a small tidal creek at 0·29 m msl.

Dese. This tidal freshwater marsh located near the mouth of the Dese River receives sediment input from the river and is composed of nearly pure stands of *Phragmites australis*. Two sites were established, one on the edge of a tidal creek about 300 m from the river (Dese 1, 0·29 m msl) and a second on the edge of the river (Dese 2, 0·36 m msl).

Tessera. This salt marsh is located on the western edge of the lagoon adjacent to Marco Polo airport and is experiencing edge erosion due to wave attack. The vegetation in the area is composed of *A. fruticosum*, *P. palustris* and *L. serotinum*. Two sites were established in this area at 0·38 m msl (Tessera 1 and 3).

Torson di Sotto. This site is in a constructed wetland in the southeastern lagoon formed when dredged spoil was pumped into a confined area in 1992. By 1995, the area was sparsely covered with *A. fruticosum*. Sites were established in the constructed wetland (Torson 2, 0·40 m msl) and in an adjacent natural wetland dominated by *P. palustris*, *L. serotinum* and *A. fruticosum* (Torson 1, 0·39 m msl).

Punta Cane. This area is an eroding wetland in the southern part of the lagoon in an old delta of the Brenta River where there has been rapid wave erosion and expansion of the tidal channel network during this century. Wetland vegetation includes *A. fruticosum*, *P. palustris* and *L. serotinum*. The marsh edge is being eroded by wind waves (Day *et al.*, 1998) and two small tidal channels about 10 m long are cutting into the marsh. A site was established in the marsh within 30 m of the eroding marsh edge at an elevation of 0·44 m msl. Soil elevation change stations were established about 4 m in front of the marsh where erosion is taking place (at about −0·35 m msl). Because of the high rate of shoreline erosion, a number of marker stakes were placed along the vegetation edge to determine horizontal erosion rates of the marsh edge and the enlargement of the tidal channels.

Methods

At each study area, a 50 × 50 m site was marked off in a representative area of the marsh, and duplicate, randomly-placed 4 × 4 m plots were established within the site for measurement of short-term sedimentation patterns, vertical accretion, and change in soil surface elevation. Short-term sedimentation was measured from March 1993 to May 1996 as the accumulation of material on 9 cm Whatman ashless filters placed on the marsh surface as described by Reed (1992). Three pre-weighed, numbered filters were placed in each plot at various times throughout the study period and left in place for 2–4 weeks. After collection, the filter pads were dried at 60 °C for 48 h and weighed to obtain total sedimentation. When parts of filters were lost, the percentage area lost was estimated and corrected for this. The filters were then combusted at 550 °C and re-weighed. The loss on combustion was considered organic matter and the material remaining was inorganic. Because measurements were made on a short-term basis and the periods of collection were chosen to encompass the range of events that affect sediment mobilization and deposition on the marsh surface, the effect of these events (such as storms, high river flow, rainfall, as well as calm periods) could be determined (Reed, 1992).

The short-term sedimentation study represents a completely randomized block design, with time (sampling periods) as the blocking factor, considered a fixed effect. The study comprised 10 sites and 13 sampling periods for a total of 580 observations. The analysis was conducted using SAS Proc Mixed (SAS, 1990) to handle the unbalanced data and nested error structure. A log transformation de-emphasized near-zero observations and the influence of infrequent high observations (which represent very important phenomena in the sedimentation budget). *Post hoc* contrasts compared marginal means of sites (protected at the 0·05 family-wise Type I error rate by a Bonferonni adjustment). For those sampling periods that showed significant differences between sites, contrasts were made comparing those in high-energy environments (decided *a priori*, Dese 1 and 2, Laghi and Punta Cane) with the others (also protected by Bonferonni adjustment).

Vertical accretion was measured as the accumulation of material over 0·25 m^2 artificial marker horizons laid down on the marsh surface as described by Cahoon and Turner (1989). Three horizons were randomly laid down in each plot for a total of six markers. The markers were set up in March 1993 and sampled by coring every six months until April 1996. The markers in the constructed wetland had eroded away after three months, so no further measurements were taken. Soil elevation changes were measured using a sedimentation-erosion table (SET) developed for high precision measurements (± 2 mm) of surface elevation in wetlands (Boumans & Day, 1993). One SET station was established in each marsh plot (Figure 1) and surface elevation was measured at approximately three month intervals until April 1996. SET stations were also established (February 1994) on the eroding marsh front at Punta Cane which had been denuded of vegetation. Soil organic content was evaluated by ignition loss from three soil cores (upper 5 cm) taken from each station. Bulk density was determined from three to five small cores (2 cm diameter) 5 cm deep taken at each site. The data from the cores were ln transformed because they were not normally distributed and differences between sites were tested with a two-way ANOVA.

The sedimentation-erosion study followed a repeated measures design with a nested error structure. Elevation was measured at 11 time intervals (approximately every three months) over three years at each of 10 sites and resulted in 720 observations. Two SET pipes were established at each site, which represents a low sample size. Analysis of variance conducted within the repeated measures design tested if the variance between SET pipes at each site was equal to the variance between orientations ($n = 4$) within a SET pipe (SAS Proc GLM; SAS, 1990). The design of the SET is such that for each pipe, elevation is measured with nine pins on an arm which is placed in four different orientations (see Boumans & Day, 1993 for a detailed description). An assumption of the analysis was that the measurements at each level (pins, orientations and SET pipes) were independent. The results showed that for all sites, the variance components were not significantly different at $P > 0{\cdot}14$. Because of this, we pooled the two set pipes at each site, resulting in an effective sample size of eight (eight orientations). The repeated measures model was changed to reflect this conceptual design change. Since the test for parallel trends among all sites over time was significant (non-parallel), univariate analyses were conducted on each time period and pairwise comparisons were made between sites, using a Bonferonni family-wise error rate.

The analysis of accretion over marker horizons was also conducted as a repeated measures model with a nested error structure, since the same sediment

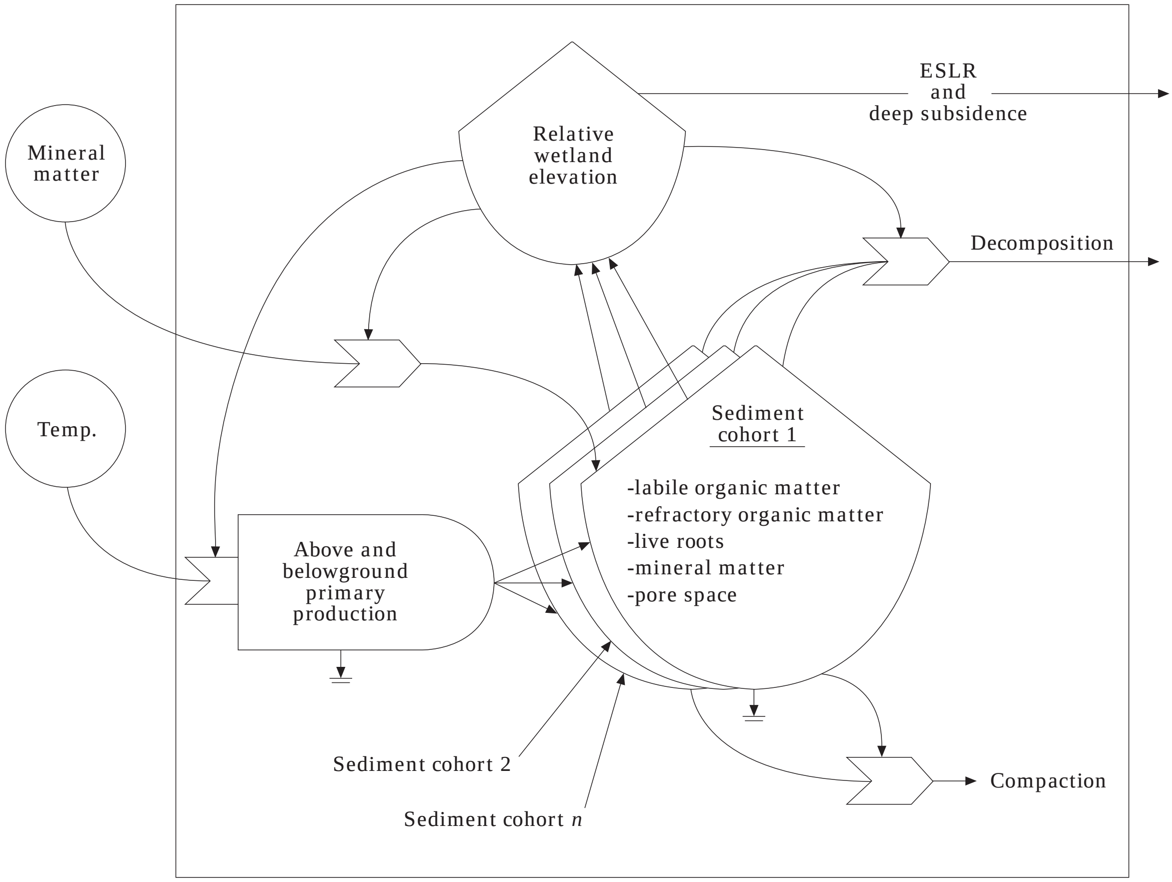


FIGURE 2. Conceptual model diagram showing the three sub-models, forcing functions and field data inputs. Modified from Rybczyk *et al.* (1998).

surface was sampled in each of six sampling dates spread over a period of 35 months. The data set comprised 392 observations. Since the test for parallel trends among sites was significant, univariate analyses were conducted on each time period and pairwise comparisons were made between sites, using a Bonferonni-adjusted family-wise error rate.

The sediment elevation measurements, averaged per site, were regressed on corresponding accretion to estimate the percentage of variation in total soil elevation change that could be explained by a linear trend in accretion (Proc GLM; SAS, 1990). The analysis was limited to dates and sites held in common: May–June 1994, January 1995, June–August 1995 and January–February 1996; Dese 1 and 2, Laghi, Punta Cane 1, San Felice 1 and 3, Tessera 1 and 3 and Torson 1.

Shallow subsidence was calculated for each plot following the approach of Cahoon *et al.* (1995*b*). Because of shallow subsidence, net soil elevation change measured by the SET rather than vertical accretion as measured by marker horizons must be used to determine the rate of vertical growth. Therefore, current soil elevation change was compared with the present (2·4 mm yr^{-1}) and predicted (5·0 mm yr^{-1}) rates of RSLR for Venice Lagoon (as documented in the introduction) to determine how net elevation change compared to RSLR. If there is an elevation deficit (surface elevation gain <RSLR), the site will become progressively more waterlogged and vegetation increasingly stressed. The time course of elevation at each site was investigated further using the wetland elevation model described in the next section.

Modelling

Model development

The integrated model consists of three linked sub-models or sectors: (a) primary productivity; (b) sediment dynamics and (c) relative soil elevation (Figure 2). Numerous field measurements (Day *et al.*, 1995*a*; Scarton & Rismondo, 1996), were used for model initialization, calibration and validation. Specifically, measurements of annual above and belowground production and turnover were used to calibrate and initialize the production submodel, decomposition experiments and soil core analyses were used to calibrate the sediment dynamics submodel and marker horizons were used to estimate mineral inputs. We programmed the model using STELLA® iconographic modelling software. An Euler numerical integration method, with a $\Delta t = 1$ week, was used to solve the finite difference equations generated by the STELLA software. State variable differential equations are described in Table 1. A full description of the generic model, including validation and calibration exercises and sensitivity analyses, are provided by Rybczyk *et al*. (1998). A brief description of the model and modifications to the published model are provided in the following sections.

Primary productivity submodel. *In situ* organic matter (o.m.) production is simulated in this submodel as a function of wetland elevation. The simulated o.m. is allocated to the sediment dynamics sub-model, either on the surface, as litter, or within the soil column as root biomass. There are two state variables in this submodel, *leaf* (aboveground biomass) and *root* (belowground biomass) (Table 1). These state variables are a function of five rates: (a) net primary production (*maxnet*), (b) leaf litter production during the growing season (*llitrateg*), (c) leaf litter production at the end of the growing season/beginning of the dormant season (*llitrated*), (d) root litter production (*rlitrate*) and, (e) root to shoot ratio (*rootmult*). Belowground production is a function of aboveground biomass. Litter production for both state variables are calibrated to reflect field measurements (Scarton & Rismondo, 1996).

Because there is no linked hydrology or salt conservation model, elevation acts as a surrogate for salt and hydrologic stress on vegetation production in the wetland elevation model. In Venice Lagoon salt marshes, certain plant species associations have been shown to be characteristic of given elevation ranges (Pignatti, 1966—see Area Description, Table 2). For all but the Dese site we ascribed four plant community associations to the elevation ranges 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm, respectively, each with specific net primary production, litter production and turnover characteristics (Table 2). Changes in these characteristics are triggered and simulated by making the five rates, described in the previous paragraph, an instant step function of elevation. In reality, vegetation shifts occur more gradually over several years, but it is believed that this does not introduce serious errors in the model which has a simulation time of 100 years. This issue is addressed in more detail in the discussion. In general, simulated above and belowground production, as well as mean standing crop, decrease with decreasing elevation. Additionally, at the lowest elevations, the dominant plant species are annual instead of perennial, therefore, there is no live overwintering belowground biomass. At the Dese site, strong freshwater riverine inputs maintain a near-freshwater plant community dominated by *P. australis*. For this reason, it is assumed that this community will persist and that there will be a simple decrease in primary production as elevation decreases to zero.

Sediment dynamics submodel. The sediment dynamics submodel has four state variables representing labile o.m., refractory o.m., mineral matter and live root biomass distributed among a number of sediment layers or cohorts (Table 1). Sediment state variables are passed from cohort to cohort according to the following simulated yearly time sequence; 1 (surface cohort), 1, 5, 5, 5, 5, 10, 10, 10, 10, 10, 10, 10, 10, 10, 20, 20 and 20+ (deepest cohort) years. Thus short term sediment processes, most of which occur near the sediment surface, are simulated within the cohorts with the shortest retention period. This allows for precise calibration and resolution of output. Deep sediment process, which for the most part occur at decades-long time scales, are simulated within the cohorts with the longest retention time.

Maximum mineral inputs are the only forcing functions in this submodel, as other inputs are model generated. This submodel simulates decomposition of o.m., inputs of mineral matter, the distribution of root biomass, sediment compaction, and the transfer of material from cohort to cohort. 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 each sediment cohort, due to 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 the mass of material above a particular cohort. This sector is particularly powerful, because the measurements obtained from a few soil cores (bulk density, and % organic and mineral matter) along with measurements of accretion rates, (e.g. ^{210}Pb and marker horizons) provide a comprehensive set of data which can be used to calibrate the submodel at several points. Critical algorithms for this submodel are described below.

Decomposition: The model separates all o.m. into labile and refractory pools, each with its own time dependent decay rate. Additionally, the labile o.m.

TABLE 1. State variables and differential equations for the Integrated Wetland Elevation Model

Labile organic matter sediment cohorts , lab_below_n

$d(lab\_below_n)/dt =$	$(litter \times leaf\_lab\_frac) + (rlit_n \times rlab\%) + (tranl_{n-1} \times lab\_below_{n-1}) - lab\_below_n \times klab) - (tranl_n \times lab\_below_n)$
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)
$tranl_{n-1}$	transfer rate of labile o.m. from overlying cohort (g C cm^{-2} yr^{-1})
lab_below_{n-1}	labile o.m. in overlying cohort (g C cm^{-2})
$klab$	decomposition rate of labile organic matter (week^{-1})
$tranl_n$	transfer rate of labile o.m. to underlying cohort (g C cm^{-2} yr^{-1})

Refractory organic matter sediment cohorts, ref_below_n

$d(ref\_below_n)/dt =$	$(litter \times (1 - leaf\_lab\_frac)) + (rlit_n \times (1 - rlab\%)) + (tranr_{n-1} \times ref\_below_{n-1}) - (ref\_below_n \times kref) - (tranr_n \times ref\_below_n)$
where:	
ref_below_n	refractory o.m. in cohort n (g C cm^{-2})
$tranr_{n-1}$	transfer rate of refractory o.m. from overlying cohort (g C cm^{-2} yr^{-1})
ref_below_{n-1}	refractory o.m. in overlying cohort (g C cm^{-2})
$kref$	decomposition rate of refractory organic matter (week^{-1})
$tranr_n$	transfer rate of refractory o.m. to underlying cohort (g C cm^{-2} yr^{-1})

Mineral matter in sediment cohorts, $mineral_n$

$d(mineral_n)/dt =$	$(max\_min\_in \times minelvfunc) + (tranm_{n-1} \times mineral_{n-1}) - (tranm_n \times mineral_n)$
where:	
$mineral_n$	mineral matter in cohort n (g cm^{-2})
max_min_in	maximum mineral input as a function of elevation (unitless)
$tranm_{n-1}$	transfer rate of mineral matter from overlying cohort (g cm^{-2} yr^{-1})
$mineral_{n-1}$	mineral matter in overlying cohort (g cm^{-2})
$tranm_n$	transfer rate of mineral matter to underlying cohort (g cm^{-2} yr^{-1})

Live roots in sediment cohorts, $root_n$

$d(root_n)/dt =$	$rootin_n - (rlitrate \times root_n)$
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*

$d(leaf)/dt =$	$maxnet - (leaf \times llitrateg) - (leaf \times litrated)$
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*

$d(root)/dt =$	$rootprod - (root \times rlitrate)$
where:	
$root$	belowground live root biomass (g C m^{-2})
$rootprod$	root production rater (g C m^{-2} week^{-1})
$rlitrate$	root litter production rate (week^{-1})

TABLE 2. Generic simulated vegetation biomass parameters for the saltmarsh site switching function. Observed parameters are derived from the unpublished data of F. Scarton (pers. comm.). Observed values are reported as means ± standard deviation. Production values are reported as mean ± standard deviation (g m^{-2} yr^{-1})

Elevation	Dominant species	Parameter	Observed	Simulated
30–40	*Arthrocnemum fruticosum*	Aboveground production	666	666
	Halimione portulacoides	Belowground production	1378	1378
		Max. biomass (above)	766·9 ± 285·3	897
		Max. biomass (below)	3496 ± 2171	3429
20–30	*Limonium serotinum*	Aboveground production	307	307
	Puccinellia palustris	Belowground production	1368	1368
		Max. biomass (above)	512·8 ± 252·1	412
		Max. biomass (below)	3421 ± 1999	3953
10–20	*Spartina maritima*	Aboveground production	311	311
	Limonium serotinum	Belowground production	932	932
		Max. biomass (above)	662·4 ± 304·7	421
		Max. biomass (below)	2221 ± 1778	2652
0–10	*Salicornia* sp.	Aboveground production	307·2 ± 106·9	307
		Belowground production	100	100
		Max. biomass (above)	307·2 ± 106·9	307
		Max. biomass (below)	100	100

decomposition rate for the surface cohort is separate from the labile decomposition rate for the rest of the sediment cohorts (allowing for a distinction from leaf and root labile o.m.). Finally, there is a separate, depth dependent, decomposition rate for deep refractory material. Decomposition for each o.m. state variable in each cohort is described by a simple negative exponential ($-k$) model.

Mineral inputs: Previous models have simulated mineral inputs as a function of marsh elevation and tidal range (French, 1993; Callaway, 1994) and we use a similar approach. For Venice Lagoon there is a relationship between wetland elevation and inundation frequency (Figure 3). At each site, baseline annual mineral inputs for a given elevation were derived from marker horizon data. Using these data, maximum inputs (at elevation = 0) are calculated using the curve shown in Figure 3. Mineral inputs (*minin*), as a function of elevation, can then be calculated for any elevation according to the equation:

$$minin = max\_min\_in \times minelvfunc \qquad (1)$$

where:

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

minelvfunc = (0·007(relative_el^2) − 1·603(relative_el) + 81·33/81·33) (unitless between 0 and 1)

Note: the equation: y = 0·007(relative_el^2) − 1·603(relative_el) + 81·33 yields the % of time flooded for a given elevation. If elevation = zero, then y = 1, and *minin* equals *max_min_in*.

Sediment compaction: Within the temporal bounds of this model, soil compaction is a function of:

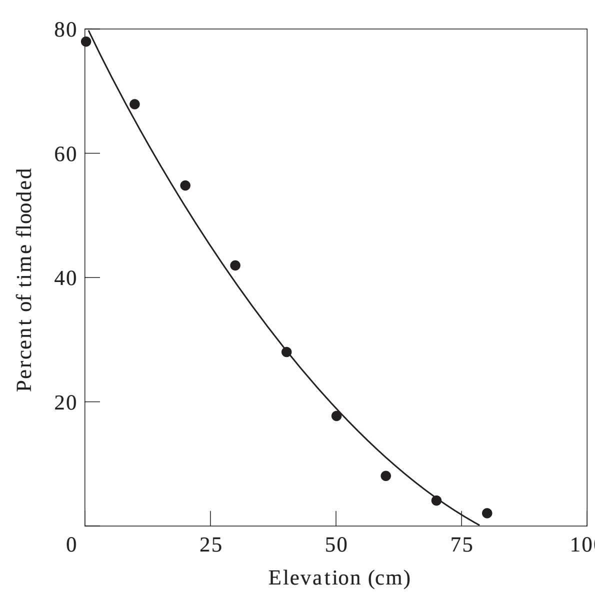


FIGURE 3. The relationship between wetland elevation and inundation in Venice Lagoon (G. Cecconi, Consorzio Venezia Nuova, unpubl. data).

(a) o.m. decomposition, simulated separately and, (b) the reduction of sediment pore space (primary consolidation) (Penland & Ramsey, 1990). Callaway *et al.* (1996) simulated the compaction of pore space as an asymptotic decrease with depth, bounded by pre-set 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:

$$porespace_n = poremin + (poremax - poremin) \times compact_n). \quad (2)$$

where:

$pore\_space_n$ = pore space of cohort n (%)
$poremin$ = minimum pore space for the entire sediment column (%)
$poremax$ = maximum pore space for the entire sedimentation column (%)
$compact_n = 1 - (tmass_i/(compk + tmass_i)$ (unitless)

The parameter, $compact_n$ describes a Michaelis–Menten type reduction in pore space where:

$tmass_i$ = mass of sediment overlying cohort n (g cm^{-2})
$compk$ = half saturation compaction constant (unitless)

Poremin, *poremax* and *compk* values are derived from site specific soil cores collected to a depth of approximately 40 cm.

Relative elevation sub-model. Wetland elevation, relative to sea level, is simulated as the balance between eustatic sea-level rise (ESLR), deep subsidence, shallow subsidence and the accretion of organic and inorganic material. The accretion of mineral matter is modelled explicitly with the *minin* function described in the sediment dynamics submodel. Inputs of o.m. are simulated in the primary productivity submodel. Shallow subsidence is modelled explicitly with separate decomposition and pore space compaction functions. The remaining two parameters that affect simulated relative elevation, deep subsidence and ESLR, are entered into the model as forcing functions.

Initialization and calibration: data required for model initialization are shown in Table 3. It is critical to note that the only data required for model calibration include annual accretion and, most critically, sediment bulk density, % organic matter, % mineral matter and pore space with depth. Calibration procedures are described in detail by Rybczyk *et al.* (1998).

Simulation scenarios: for all sites we first ran the model for 200–300 simulated years, to allow the model to generate a stable simulated soil column. Output from this ‘ pre-simulation ’ was then used to initialize the sediment column state variables for future simulations. To simulate and predict wetland sustainability over the next 100 years at all sites, we used as forcing functions, estimates of deep subsidence from Carbognin *et al.* (1996) and two IPCC eustatic sea-level rise scenarios over the next 100 years: (a) ‘ current trends ’ of 15 cm and, (2) ‘ best estimate ’ of 48 cm (Gornitz, 1995). Additionally, by systematically varying simulated mineral inputs to each site, it was possible to estimate the amount of additional mineral sediments required to maintain wetland elevation under both IPCC scenarios.

Results

Short term sedimentation on the filter pads at the different sites was highly variable, ranging from 0·1 to 73 g m^{-2} day^{-1} (Figure 4). This high variability reflected the importance of high energy events, such as strong storms and river floods, in mobilizing and transporting sediments. Significant differences between sites existed for all sampling periods except May 1993, August 1994 and April 1995. The contrast between high energy sites and low energy sites was significant only in October and November 1993, November 1994 and January and November 1995. These sampling periods occur in the late autumn-early winter, a period characterized by strong winds and high river discharge. For example, the highest sedimentation (73·3 g m^{-2} day^{-1}) at Punta Cane in October 1993 was associated with sustained Scirocco winds of 60 kph and the highest tides recorded in the last 10 years. The material deposited in the filters was 27·7–32·4% organic matter. High sedimentation rates associated with storms also occurred at Tessera and Laghi; and at Dese associated with river floods prior to the November 93 and May 94 samplings (Figure 4). The lowest mean values (1·7 and 2·2 g m^{-2} day^{-1}) occurred at San Felice. Short term sedimentation was uniformly low at this site (always less than 5 g m^{-2} day^{-1}) suggesting that high energy events do not promote sediment input to this area (Figure 4). This is likely partially the result of the jetties in the Lido inlet which restrict the input of sediments from the near shore Adriatic. Thus, this deteriorating salt marsh has very low sediment input.

Soil elevation change showed significant differences among sites over all sampling periods. As with short term sedimentation, high variability resulted in a lack

TABLE 3. Initialization parameters for Integrated Elevation Model

Symbol	Description	Units	Laghi	San Felice 1	San Felice 2	Torson 1	Punta Cane	Dese	Tessara 1
init_elev	initial wetland elevation	cm	29	33	30	39	43	29	39
min_in	current mineral inputs	g cm^{-2} $week^{-1}$	0·0025	0·0020	0·0017	0·0015	0·0074	0·0031	0·0023
max_min_in	maximum mineral input	g cm^{-2} $week^{-1}$	0·0122	0·0125	0·0088	0·0142	0·09974	0·0149	0·0212
surate	local deep subsidence rate	cm yr^{-1}	0·075	0·15	0·15	0·05	0·125	0·075	0·025
poremax	max. fraction of pore space	%	79	73	78	0·80	86	82	80
poremin	mini. fraction of pore space	%	55	43	39	78	79	76	63
comp_k	soil compaction half. sat.	g cm^{-2}	10	8	1	50	3	2	8
kdeep	decomp. rate of deep refractory o.m.	$week^{-1}$	0·0005	0·005	0·0003	0·0004	0·0001	0·0005	0·0003
klab	decomp. rate of labile o.m.	$week^{-1}$	0·05	0·05	0·015	0·05	0·05	0·046	0·05
klabsurf	decomp. rate of surface labile o.m.	$week^{-1}$	0·05	0·05	0·031	0·05	0·05	0·046	0·05
krefr	decomp. rate of refractory o.m.	$week^{-1}$	0·0025	0·002	0·0015	0·0025	0·0015	0·0015	0·0025
leaf_lab_frac	labile % of aboveground biomass	%	60	50	50	60	60	33	60
maxnet	max. net aboveground production	g C m^{-2} $week^{-1}$	4·7	10·6	10·6	10·6	10·6	10·6	16·9
rlab%	labile % of live roots	%	30	50	20	30	20	20	30
root_k	root distribution constant	cm^{-1}	0·11	0·20	0·08	0·06	0·05	0·08	0·05

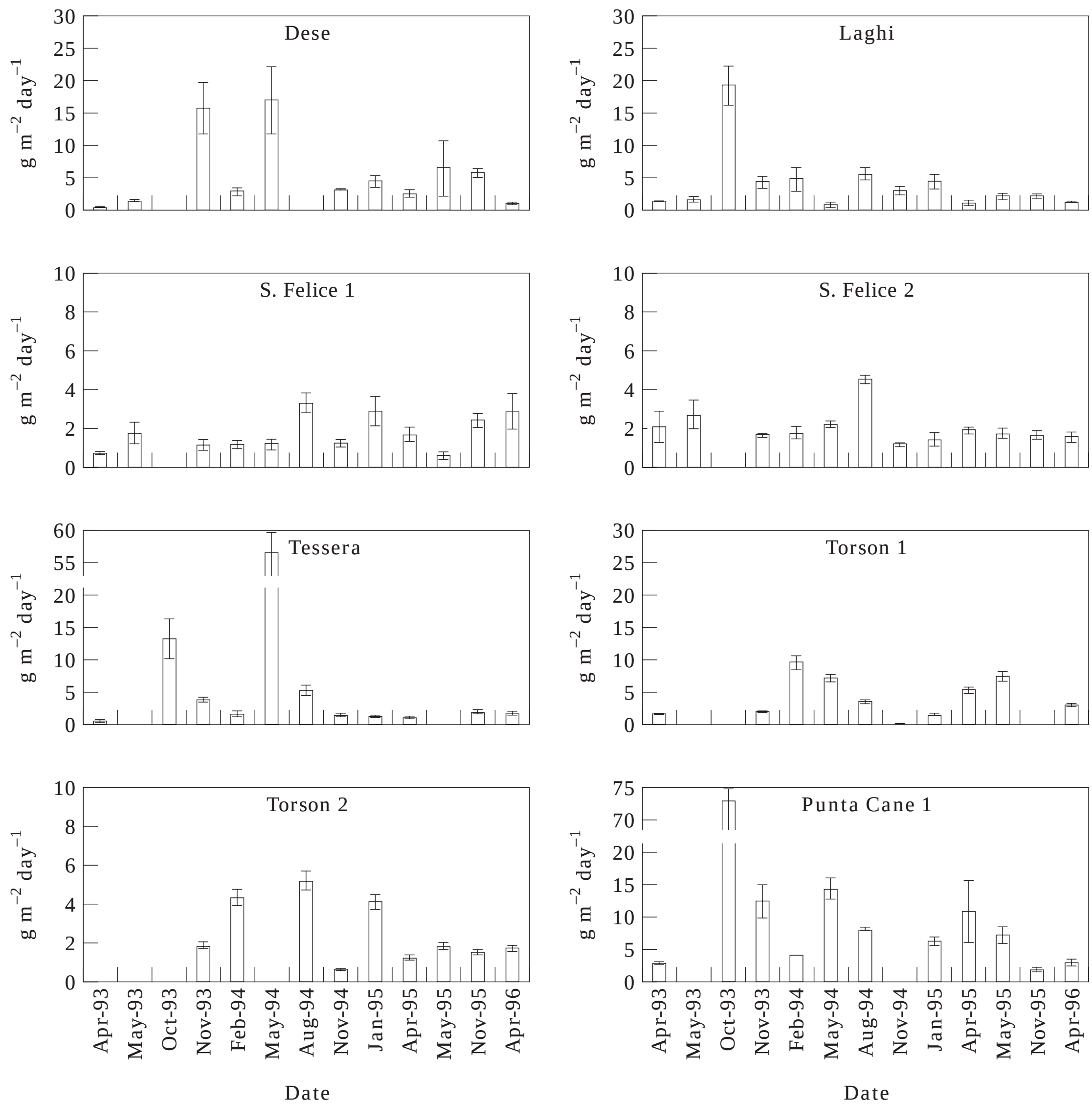


FIGURE 4. Short-term sedimentation rates at the different sites. Results for Dese 1 and 2 and for Tessera 1 and 3 are combined. Vertical lines are ± one standard error. Note different scales for San Felice 1 and 2 and Torson 2.

of consistent trends over time (Figure 5). No significant differences existed between the high energy sites and the low energy sites as groups. The only trends were with individual sites; Punta Cane 2 and Torson 2. Torson 2 (the constructed wetland) and Punta Cane 2 (the eroding mudflat in front of the marsh) had consistent elevation loss, always greater than the other sites (adjusted $P<0{\cdot}05$). Punta Cane 1 had the highest soil elevation change at the end of three years (5·88 cm). At the end of two years, the high energy sites averaged $0{\cdot}89 \pm 0{\cdot}29$ cm yr^{-1} (±1 standard error), $0{\cdot}61 \pm 0{\cdot}09$ cm yr^{-1} not considering Punta Cane 1. The remaining sites (not including Punta Cane 2 or Torson 2) averaged $0{\cdot}36 \pm 0{\cdot}06$ cm yr^{-1}.

Vertical accretion at the high energy sites (Dese, Laghi and Punta Cane 1) was always greater than at the other sites (San Felice, Tessera, and Torson 1) throughout the study period ($P<0{\cdot}0037$) (Figure 5). After 35 months, the high energy sites averaged $0{\cdot}99 \pm 0{\cdot}0{\cdot}4$ cm yr^{-1}, compared to $0{\cdot}38 \pm 0{\cdot}06$ cm yr^{-1} for the other sites. These results compare very well to those of sediment elevation. Generally, trends are more apparent in accretion than in sediment elevation, since the latter is a combination of other factors which each contribute to the overall variance of the measurements. The difference between the high energy sites and the others was mainly attributed to Punta Cane 1, which showed significantly greater

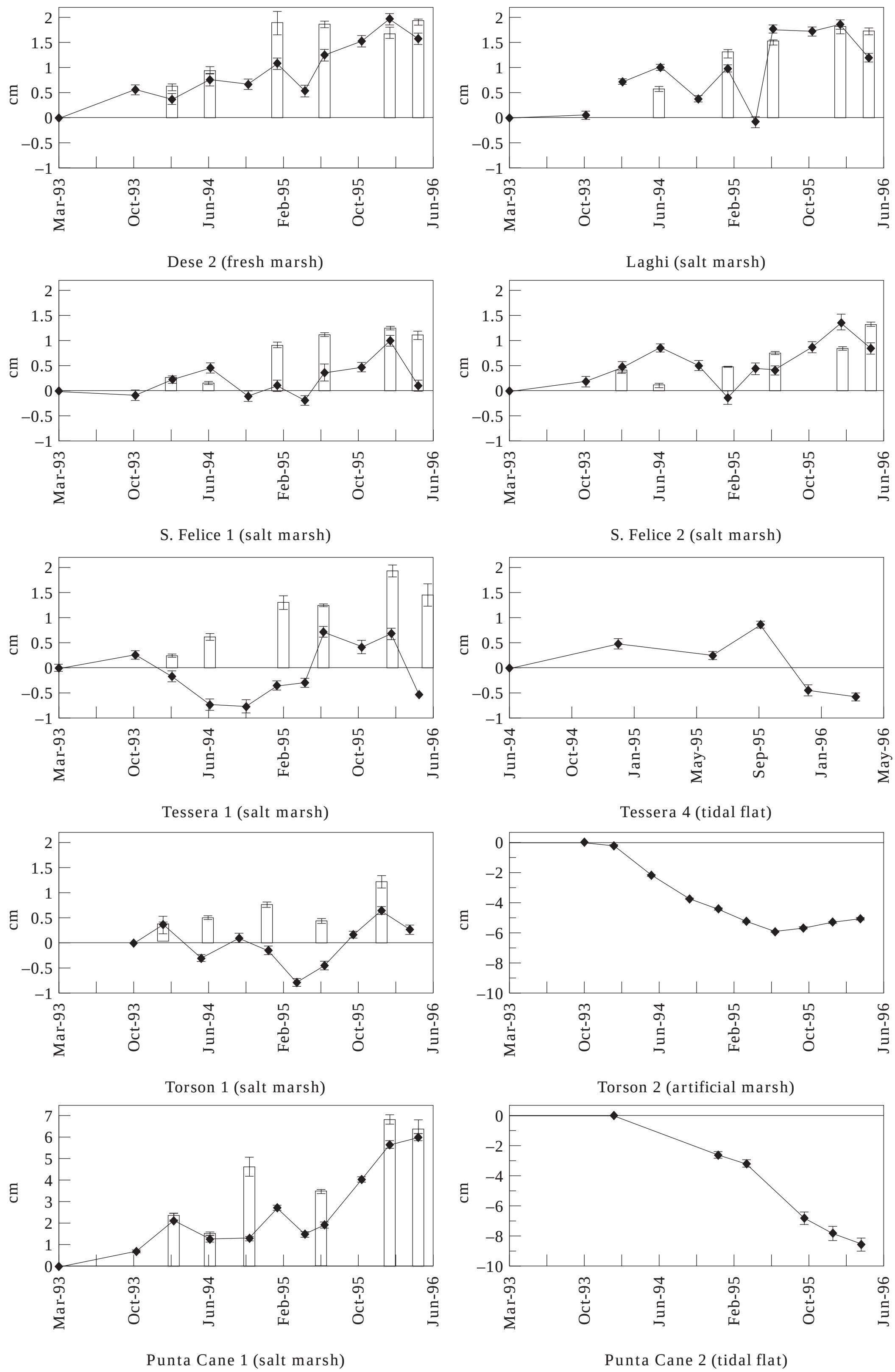
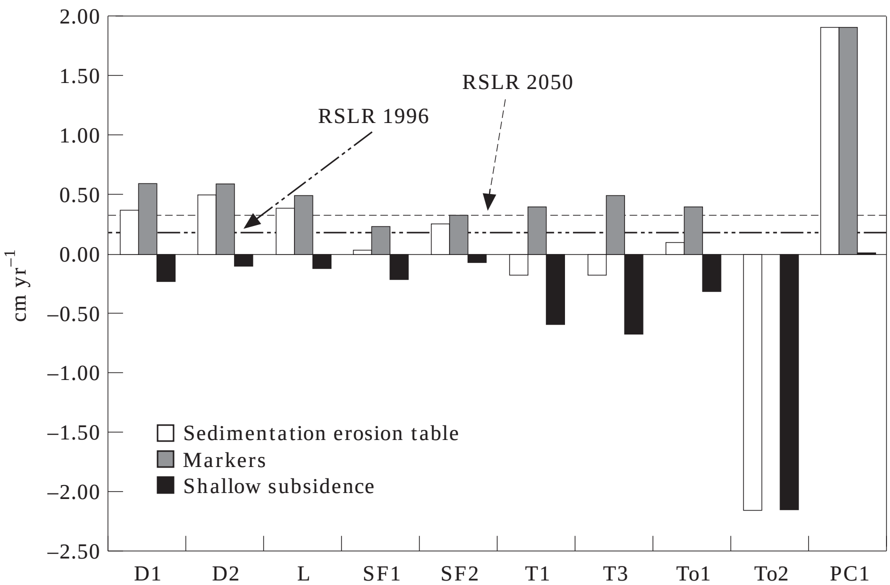


FIGURE 5. Vertical accretion (bars) and soil elevation change (line with solid squares) for the different sites (results for Dese 1 and Tessera 3 are not shown but are very similar to the data presented). O elevation is the beginning elevation at each site. Tessera 4 and Punta Cane 2 are intertidal mudflats. Torson 2 is a marsh constructed from dredge spoil material. Marker horizons to measure accretion at this site were eroded away by waves after three months. Vertical lines are ± one standard error.



D1 = Dese 1, D2 = Dese 2, L = Laghi, SF1 = S. Felice 1, SF2 = S. Felice 2, T1 = Tessera 1,
T2 = Tessera 2, To1 = Torson 1, To2 = Torson 2, PC1 = Punta Cane 1

FIGURE 6. A comparison of soil elevation change, vertical accretion, and shallow subsidence at each of the sites. The dotted horizontal line is the current rate of relative sea-level rise (RSLR) and the darker, dashed horizontal line is the estimated rate of RSLR for 2050 based on the later IPCC estimates.

accretion than the other sites for most time periods across the 35-month study. Only Dese 2 and Tessera 1 had similarly high accretion in the June 1994 sampling, over the same time in which Punta Cane had significant erosion. The strength of the linear relationship between total soil elevation change and total accretion generally increased over time. After four months, only 17·4% of the total variation in sediment elevation could be explained by the linear regression. After two years, the R^2 rose to 0·86.

At the end of three years, surface elevation increase was in all cases less than vertical accretion, indicating that accreted material was compacting and consolidating due to shallow subsidence (Figure 6). The present rates of elevation gain at San Felice 1, Tessera, and the natural Torson site are less than present rates of RSLR. The rate at San Felice 2, 0·24 cm yr^{-1}, is slightly higher than the present rate of RSLR. The present rates of elevation gain at Laghi, Dese and Punta Cane are higher than RSLR predicted for 50 years. The marsh at Punta Cane has a very high rate of surface elevation gain which is greater than the upper limits predicted by the IPCC. This site, however, is eroding rapidly and the study plots will be eroded within 15–25 years.

The edge of the marsh at Punta Cane is experiencing a rapid retreat due to wave induced erosion. The vegetation edge retreated at a rate of 1·2–2·2 m yr^{-1}. The two tidal channels are lengthening by 0·2 and 0·6 m yr^{-1} and widening by 0·48 and 0·26 m yr^{-1}, respectively. We observed distinct depositional layers in the exposed vertical erosional surface on the edge of the tidal channel. Material of relatively recent origin such as plastic sheeting was buried 30–50 cm indicating that this marsh formed rapidly over the past several decades by vertical accretion.

The results of the soil analysis show a clear difference between the natural marshes and the constructed one, which had a higher fresh weight (2·1 *vs* 1·25 to 1·49 g cm^{-3} for the natural marshes), lower water content (25·4 *vs* 47·6 to 72%), lower organic matter (10·8 *vs* 18·3 to 26·6%) and higher bulk density (1·6 *vs* 0·36 to 0·8 g cm^{-3}). Among the natural marshes, there was no difference in fresh weight ($F_{6,38}$ = 2·00, NS) whereas there was a highly significant difference in organic matter ($F_{6,38}$ = 16·77, P < 0·001) and bulk density ($F_{6,38}$ = 6·00, P < 0·001). Overall, the riverine site with *P. australis* had higher water content (72·0%) and lower bulk density (0·33 g cm^{-3}) than the salt marsh sites. Of the natural salt marshes, the higher site at San Felice (site 1) had the highest bulk density (0·50 g cm^{-3}) and the lowest water (47·6%) and organic matter (24%) content.

TABLE 4. Number of years to wetland submergence (wetland elevation relative to sea level = 0), given a 100 year simulation, under various IPCC ESLR scenarios. ' Declining ' indicates that although wetland elevation is decreasing, elevation does not reach zero within a 100 year time frame

	Number of years to submergence	
Site	IPCC ' Current conditions '	IPCC ' Best estimate '
Laghi	Declining	82
San Felice 1	Declining	75
San Felice 2	Declining	63
Tessera 1	Relative elevation is stable	Declining
Torson 1	Relative elevation is stable	Declining
Punta Cane	Relative elevation is stable	Relative elevation is stable
Dese	Relative elevation is stable	Declining

Model output

Eustatic sea-level rise scenarios

Given the IPCC ' best estimate ' (BE) ESLR scenario of 48 cm in the next 100 years, only Puna Cane could maintain its elevation relative to sea level. Under the IPCC ' current conditions ' (CC) ESLR scenario of 15 cm in the next 100 years, the elevation at four sites remained above sea level for the entire simulation period; Tessera 1, Torson 1, Punta Cane and Dese. Simulation results from each site are discussed separately below.

Under CC, simulated wetland elevation at Laghi declines relative to sea level over 100 years, but does not fall below 0 cm MSL during that time period. Under BE, simulated wetland elevation falls below sea level in 82 years (Table 4 and Figure 7). This site is especially vulnerable to loss because the initial elevation is already low relative to other wetlands in the Lagoon, subsidence is moderately high, and mineral inputs and organic matter production are intermediate to low compared to other sites (Table 3).

At both San Felice 1 and 2, simulated wetland elevation under CC declines relative to sea level over 100 years, but does not fall below 0 cm MSL during that time period. Under BE, simulated wetland elevation falls below sea level in 75 years for San Felice 1 and in 63 years for San Felice 2 (Table 4 and Figure 7). The model indicates that both sites are vulnerable due to low mineral inputs and high rates of subsidence (Table 3).

At Tessera 1, simulated wetland elevation at this site is stable over 100 years under the CC scenario. Under BE, simulated wetland elevation declines relative to sea level over 100 years, but does not fall below 0 cm MSL during that time period (Table 4 and Figure 7). Although mineral inputs are low at this site (Table 3), the initial elevation is high and subsidence rates are also low, thus countering a marginal accretion environment.

Under CC, simulated wetland elevation at Torson 1 is stable over 100 years. Under BE, simulated wetland elevation declines relative to sea level over 100 years, but does not fall below 0 cm MSL during that time period (Table 4 and Figure 7). Mineral inputs are low at this site, but are balanced by low rates of subsidence and a high initial elevation (Table 3).

At Punta Cane simulations indicate that wetland elevation would be stable over the next 100 years given either CC or BE scenarios (Table 4 and Figure 7). Mineral and organic matter inputs are quite high at this site, balancing both ESLR and subsidence (Table 3). However, it should be noted that this site has a high rate of shoreline erosion, a process not simulated during these exercises. Thus, even though this is the only site which is stable vertically, it will most likely erode completely within a few decades.

Finally, under CC, simulated wetland elevation at Dese is stable over 100 years. Under BE, simulated wetland elevation declines relative to sea level over 100 years, but does not fall below 0 cm MSL during that time period (Table 4 and Figure 7). This site is moderately stable due to high initial elevation and high rates of mineral inputs which balance intermediate rates of subsidence (Table 3).

Estimates of mineral inputs required for marsh survival

Only one site, Punta Cane, required no additional mineral inputs for both ESLR scenarios. Three other sites required no further inputs under the CC scenario; Tessera 1, Torson 1 and Dese (Table 5). Under the CC scenario, the amount of additional mineral sediment required to maintain elevation in the

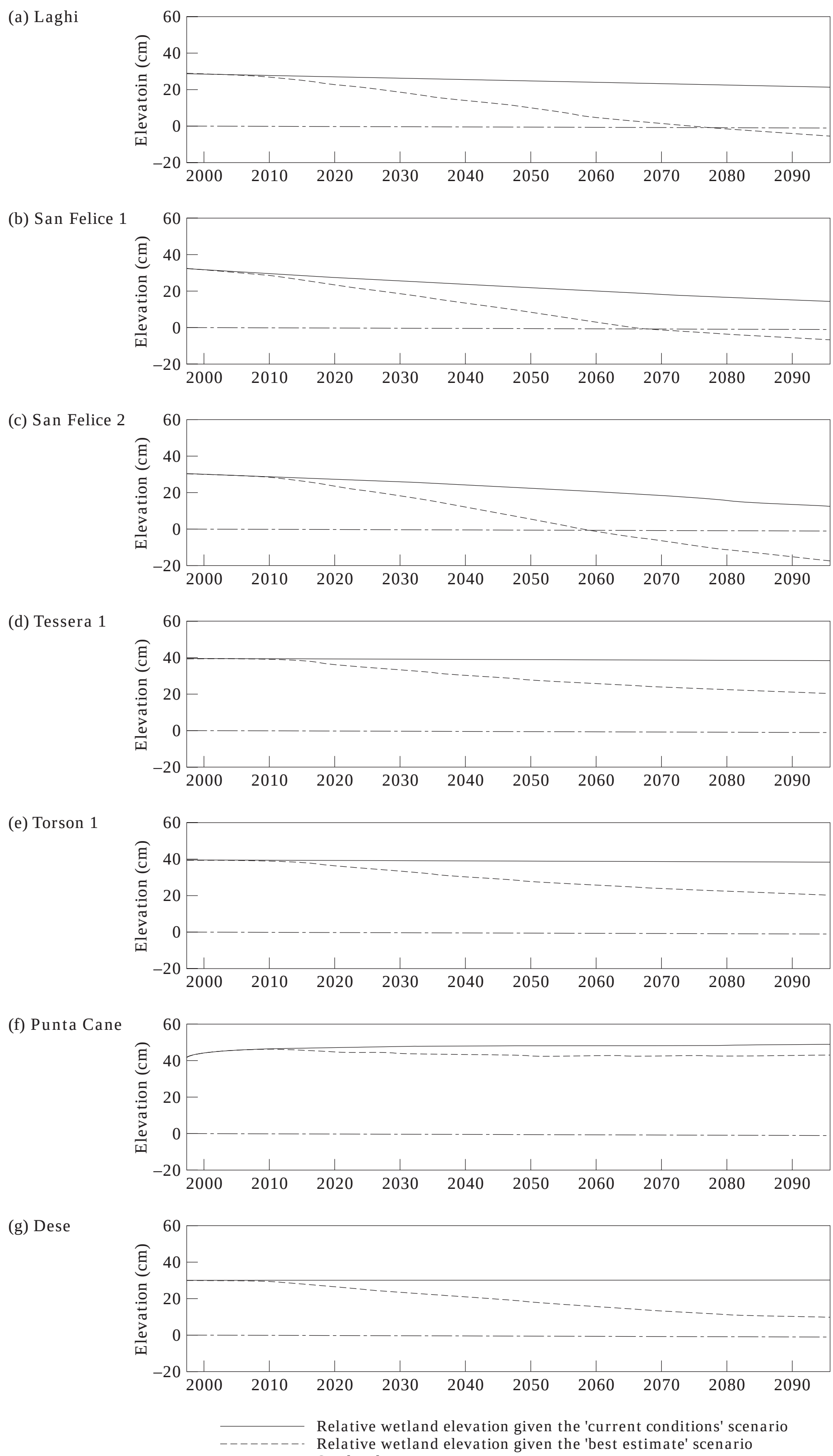


FIGURE 7. Wetland elevation relative to sea level in the next 100 years for two IPCC eustatic sea-level rise scenarios: (1) Current conditions = 15 cm sea level rise (solid line) and, (2) best estimate = 48 cm sea level rise (dashed line). Wetland elevation is plotted relative to sea level, therefore sea level appears constant (shown as dashed and dotted line).

TABLE 5. Predicted mineral inputs required over the next 100 years to maintain wetland elevation under two IPCC ESLR scenarios. All units are g dry wt. m^{-2} yr^{-1}

Wetland	Actual mineral inputs (1993–1996)	Mineral inputs required to maintain elevation under various ESLR scenarios	
		IPCC Current conditions[a]	IPCC Best estimate[b]
Laghi	1318	3325	10 985
San Felice 1	1052	7035	16 727
San Felice 2	905	6749	20 527
Tessera 1	1202	No additions required	6806
Torson 1	800	No additions required	6352
Punta Cane	3838	No additions required	No additions required
Dese	1611	No additions required	5162

[a]Current conditions: 15 cm ESLR in the next 100 years.
[b]Best estimate: 48 cm ESLR in the next 100 years.

non-stable sites ranged from 2·5 to 7·9 times the current inputs. Under the BE scenario, additional mineral sediments required to maintain elevation ranged from 3·2 to 22·6 times the current inputs.

Discussion

The patterns of soil accretionary dynamics in Venice Lagoon reflect variability in sediment supply, hydrodynamic energy, sediment consolidation and relative sea-level rise and are consistent with trends observed in other areas. During this century there has been a relative increase in water level due to eustatic sea level rise, subsidence, and deepening of the lagoon (Cavazzoni & Gottardo, 1983; Sestini, 1992). This had led to both greater wave energy and a larger tidal prism, both of which have affected the sediment dynamics and geomorphology of wetlands.

Short-term sedimentation patterns were highly variable with peak rates over an order of magnitude greater than the lowest ones. This high variability resulted because most sediment deposition on the marsh surface was associated with high energy events such as storms or river floods, as has been reported for the Mississippi delta, the Rhone delta, south-east England and other areas (Stumpf, 1983; Baumann *et al.*, 1984; Reed, 1989; Pethick, 1992; Day *et al.*, 1995*b*). The highest short-term sedimentation rates occurred at Punta Cane during strong storms while the lowest rates occurred at San Felice. Our rates were comparable to values reported elsewhere. In the Mississippi delta, mean rates ranged from 0 to 40 g m^{-2} day^{-1} (Reed, 1989, 1992; Boumans & Day, 1994) where the highest rates occurred near the coast and during frontal passage and the lowest rates occurred in impounded marshes. Short term sedimentation associated with Hurricane Andrew was as high as 130 g m^{-2} day^{-1} in the Mississippi delta (Cahoon *et al.*, 1995*b*). In the Rhone delta, short term sedimentation ranged from <1·0 to 95 g m^{-2} day^{-1} with the highest values associated with a major Rhone River flood and high winds (Day *et al.*, 1995*b*; Hensel *et al.*, 1998, 1999).

The results for most sites also showed very dynamic marsh surfaces with increases in elevation and accretion followed by decreases, sometimes by more than a cm during one sampling interval. Similar findings have been reported from the Mississippi delta (Baumann *et al.*, 1984; Reed, 1992; Boumans & Day, 1994), Delaware (Stumpf, 1983) and south-east England (Pethick, 1992). Pethick (1992) reported that the surface of saltmarshes in south-eastern England increased by 1·4 cm yr^{-1} and the mudflat in front of the marsh eroded by a similar amount; erosion of the marsh surface was as high as 0·5 cm during strong storms. Hartnall (1986) reported seasonal changes in the surface elevation of a salt marsh at Lincolnshire, U.K., of up to 3·0 cm yr^{-1} with increases in the summer and decreases in the winter. These changes were attributed to seasonal growth and decay of marsh vegetation as well as to sediment input and the highest rates of elevation gain were in areas with a high density of tidal channels. Baumann *et al.* (1984) also reported erosion of the marsh surface in the Mississippi delta. SET results from other areas almost always show both increases and decreases in marsh surface elevation, sometimes greater than 1·0 cm over several months (Childers *et al.*, 1993; Cahoon *et al.*, 1995*a*,*b* Hensel *et al.*, 1999). These changes have been attributed to storm deposition, consolidation of deposited material, seasonal patterns of root growth and decomposition and shrinking and swelling of the soil under different inundation patterns. At Punta Cane, storm deposition followed by decomposition is clearly taking place but the other factors may be important at several of the sites.

The overall average rate of vertical accretion at the different sites, which ranged from 0·3–1·9 cm yr^{-1}, is similar to values reported for other coastal wetlands. The highest rates are similar to those from the Mississippi delta where there is a high rate of geological subsidence. Cahoon (1994) reported that vertical accretion in the Mississippi delta was 0·3 cm yr^{-1} in a brackish marsh far from the coast and about 1·0 cm yr^{-1} in a marsh near the coast. Cahoon and Reed (1995) found accretion strongly related to duration of flooding in a Louisiana salt marsh, where during a stormy, high water period, accretion was 3·6 cm yr^{-1} compared to 1·08 cm yr^{-1} during a normal period. For the Rhone delta, Hensel *et al.* (1999) reported rates of vertical accretion of 0–2·5 cm yr^{-1} and in the Ebro delta, accretion ranged was 0–0·04 cm yr^{-1} (Ibañez *et al.*, 1997). In both of these cases, the highest accretion occurred at tidal riverine sites. Roman *et al.* (1997) reported that accretion in a New England back barrier salt marsh adjacent to a tidal inlet was highest during periods with major coastal storms.

In two of the sites, Punta Cane and Tessera, there was rapid shoreline erosion due to wave attack, which is common for exposed marshes (Wells, 1995). In addition, new tidal channels are forming at Punta Cane. Our measurements of shoreline retreat at Punta Cane of 1·2–2·2 m yr^{-1} compare favourably with the longer term retreat rate of 0·8–2·7 m yr^{-1} measured for marshes in the southern Lagoon between 1933 and 1970 (Cavazzoni & Gottardo, 1983). This reduction in marsh area is consistent with changes in the hydrodynamics and morphology of the lagoon (see Day *et al.*, 1998 for a more detailed discussion of the Punta Cane site). The lagoon has deepened due to RSLR and scour and, as a result, wave energy and the tidal prism have increased. Pethick (1992) has described a similar situation for marshes of the Norfolk coast in south-east England. Accelerated sea-level rise will likely lead to more rapid deterioration of the marshes at Punta Cane, Tessera and similar exposed areas in Venice Lagoon (e.g. Pethick, 1993; Wells, 1995).

Comparisons of observed and modelled results

Short-term measurements of accretion are useful because they provide critical information concerning the depositional characteristics of a given wetland (e.g. % mineral and organic matter of the deposited materials, rates of mineral deposition and the timing and magnitude of depositional events). For example, the high rates of accretion and soil elevation change measured at Dese and Punta Cane suggest that these sites have the potential for maintaining elevation as sea levels increase. However, the use of such measurements to predict long-term wetland sustainability in the face of RSLR is limited because short-term measurements of accretion do not fully integrate the long-term processes such as primary compaction and organic matter decomposition (shallow subsidence), that tend to reduce sediment volume over time (Cahoon *et al.*, 1995*b*). In contrast, sediment erosion tables, that integrate the sediment processes that contribute to shallow subsidence (Boumans & Day, 1993; Cahoon *et al.*, 1995*b*), yield measurements over time (absolute change in elevation) that can be directly compared to estimates rates of RSLR (deep subsidence plus ESLR) to determine if wetland elevation is *currently* stable, decreasing or increasing.

In Venice Lagoon, rates of soil elevation change measured with the SET were less than rates of accretion measured with feldspar horizon markers for all of the wetland sites reflecting the effects of compaction and decomposition. Comparisons of SET measurements to current rates of RSLR (Figure 6) indicate that only three wetlands, Laghi, Punta Cane and Dese are currently maintaining elevation relative to sea level. However, as noted previously, these types of direct comparisons do not take into account possible mechanisms that feedback on elevation processes over the long term (e.g. allogenic sediment deposition, decomposition and autogenic primary production).

The wetland elevation model, which does consider feedback mechanisms, indicates that given current RSLR conditions, the elevation at four wetlands; Tessera 1, Torson 1, Punta Cane and Dese will remain stable over the next 100 years and elevation will decline at Laghi, San Felice 1 and San Felice 2 (Figure 7). Why does the model predict that elevation at Tessera 1 and Torson 1 will remain stable even though current SET *vs* RSLR comparisons suggest the opposite (Figure 6). Initial elevation is relatively high at both of these sites and, consequently, mineral inputs are low, as reflected by both the accretion and SET data (Figure 5). Since material inputs are a function of elevation, as elevation decreases, simulated mineral inputs increase enough to compensate for RLSR.

In contrast to the Tessera and Torson sites, the model predicted that elevation will decrease relative to sea level at Laghi while direct comparisons of SET *vs* RSLR suggested the opposite. In this case, although *current* mineral inputs are higher at Laghi than at either Tessera 1 or Torson 2, the *potential maximum* mineral inputs are higher at Torson and Tessera because the initial elevation at Laghi is lower. Mineral inputs are currently much closer to maximum at Laghi, than at Torson and Tessera.

Soil elevation change and vegetation succession

As the marsh surface elevation at the different sites declines relative to sea level, the vegetation associations at these sites will undergo a series of changes before the marsh converts to a mudflat due to vegetation death (Pignatti, 1966, see Area description and Table 2). Although there is some elevation overlap among these associations at our sites, the vegetation shifts towards more flood tolerant plants as marsh elevation decreases. The following indicates the vegetation changes which will likely occur under the different model predictions.

The Tessera site, at 38 cm, has characteristics of the two higher elevation associations with *A. fruticosum*, *P. palustris* and *L. serotinum*. The site does not lose elevation under IPCC current conditions (CC) but declines to about 21 cm in 100 years under the IPCC best estimate (BE). Under the latter scenario, *A. fruticosum* would probably disappear, *P. palustris* will lose importance and *L. serotinum* will gain and *S. martima* will likely begin to invade. The natural marsh at Torson, at 39 cm, also has characteristics of the two higher elevation associations and is dominated by *L. serotinum* and *A. fruticosum*. Elevation remains constant under CC and falls to 17 cm under BE. *Arthrocnemum fruticosum* will probably disappear, *P. palustris* may invade and gain then lose importance and *L. serotinum* will gain. *Spartina maritima* will likely begin to invade.

The higher site at San Felice 1 has an elevation of 35 cm and the lower at San Felice 2 is at 29 cm. However, because of poor drainage, the vegetation associations are mixed, but the higher site has *A. fruticosum*, *L. serotinum* and *P. palustris* while the lower site is dominated by *S. maritima* and *P. palustris*. For San Felice 1, elevation falls to 17 cm in 100 years under CC and reaches sea level in about 75 years with BE. For the same conditions at San Felice 2, elevation is 14 cm in 100 years and sea level in 65 years. San Felice 1 will likely change to *L. serotinum* and *S. maritima* under CC and disappear in 75 years with BE. San Felice 2 will probably convert to a *S. maritima* and *Salicornia* association with CC and disappear within 65 years with BE.

Laghi, at 29 cm, will decrease to about 15–16 cm in 100 years under CC and decrease to sea level in about 85 years with BE. Presently, *J. maritimus* dominates. It will likely shift to a marsh dominated by *S. maritima* under CC and disappear in about 75 years with BE. Dese will not change in elevation under CC but will decrease to about 10 cm under BE. Under both conditions, it will remain a freshwater marsh so long as there is strong riverine influence. Punta Cane at 43 cm is the highest site studied and has vegetation of the highest elevation association. There will likely be little change in vegetation due to soil elevation changes which increase under both scenarios. But due to shoreline retreat, the measurement plots will be eroded away in 15–25 years. The high elevation community may maintain itself by migrating back at the same rate as shoreline retreat until the island fragments and disappears.

These shifts in vegetation associations have important implications for organic soil formation and total accretion. Although there is little difference between the three lower vegetation associations in aboveground production and maximum standing crop, there is a marked decrease in belowground production and peak standing crop (Table 2). For example, belowground production is about 100 $gm^{-2} yr^{-1}$ and belowground biomass is 100 $g m^{-2}$ for the lowest *Salicornia* vegetation association, while the other associations characteristic of higher elevations have values an order of magnitude higher. Thus, the belowground vegetative contribution to soil formation will decrease significantly as wetland elevation declines due to the positive feedback mechanism where decreasing elevation leads to rapidly decreasing organic soil formation.

The projected trends of succession with rising sea-levels may not occur exactly as described. Roozen and Westhoff (1985) studied trends in salt marsh succession over a 27 year period in a Dutch salt marsh where elevation was increasing. They found that ‘ successional trends are clearly directional, mainly in the lower parts of the salt marsh, where the effects of the tides is regular and predictable. In the higher parts the trends get somewhat obscured by the various interconnected but convergent pathways ’. Thus, it is believed that the predicted trends for the Venice salt marshes are likely to occur, but there may be some differences in the structure of the plant communities over the period when the marshes are submerging. It is assumed that relative water-level changes are gradual enough so that vegetation change occurs without the marsh becoming devoid of vegetation. The results of Pignatti and the vegetation composition at our sites indicate that this is the case.

The future of Venice Lagoon marshes

Compared to marshes in areas with low sea-level rise and continued sediment input, changes in the marshes of Venice Lagoon are rapid. In some coastal areas, there has been a slow but sustained vertical adjustment to eustatic sea-level rise for several thousand years (Redfield, 1972; McCaffrey & Thompson, 1980; Orson *et al*., 1987). By comparison, a number of the marshes that have been studied have much higher rates of accretion and resulting elevation increase (Laghi, Dese and Punta Cane). At Punta Cane, for example, the upper half metre of marsh has formed over 30–40 years which is consistent with a RSLR of about 30 cm or more since 1930 (Sestini, 1992; Bondesan *et al*., 1995). Despite the relatively high rate of elevation gain at some of the sites, however, model results predict that only Punta Cane has a high enough accretion rate to maintain elevation with predicted acceleration of sea-level rise.

Based on these results, the future of Venice Lagoon marshes looks bleak. If no action is taken to prevent it, the marshes at Punta Cane, Tessera, San Felice and Laghi will continue to erode due to wave attack and increasing tidal energy, perhaps at an accelerating rate as RSLR and lagoon deepening continue to increase. All marshes except Punta Cane will lose elevation if sea-level rise accelerates. The forces which have led to and continue to lead to their degradation are likely to continue in the future. There is a need to balance the strong net loss of sediments from the lagoon with sediment inputs. However, all major rivers have been diverted from the lagoon and the presence of the jetties in the inlets restricts sediment input from the nearshore zone. Frontal erosion due to wave attack is occurring for many of the lagoon marshes. As fetch increases, the strength of wave attack will increase. RSLR and wave scour will continue to deepen the lagoon leading to further export of sediments. The increasing tidal prism will lead to increased tidal energy which will continue to cause expansion of the tidal creek network and further sediment loss. The net sediment loss and lack of riverine sediment input is causing low sedimentation on marsh surfaces and most marshes are failing to keep apace of sea-level rise. When these marshes subside to a point where vegetation death occurs, sediment loss will be increased even further.

If these trends of wetland loss are to be reversed, new management approaches must be adapted. One approach is the diversion of river flow back into the lagoon. This would result in new sediment input and wetland expansion as happened when the Brenta River was diverted back into the southern lagoon from 1840–1896 to relieve flooding in agricultural land along the diversion canal. During this period about 2300 ha of coastal marsh were created in a ‘ large fluvial delta ’ (Zunica, 1974). This is equivalent to about one third of the total wetland loss during the 20th century. A practicable way to reverse wave erosion of marshes is to reduce wave energy along the marsh edge using permeable breakwaters or wave-stilling devices. Because they are permeable, they would not reduce sediment delivery to the marsh surface and would probably enhance accretion and revegetation in front of the marsh. Such breakwaters have been used successfully to establish marshes in The Netherlands and the Mississippi delta (Schoot & de Jong, 1982; Boumans *et al*., 1997). It is possible that placement of such structures could be done in a way that waves are reduced and accretion is enhanced in both the immediate vicinity of the structure but also at some distance away in adjacent areas. Such management actions should be taken as part of a holistic management strategy for the entire lagoon. A number of additional elements of such an approach have been proposed including construction of salt marshes and tidal flats with dredge material, vegetative plantings, and use of wetlands to reduce nutrient levels. Holistic management approaches have been proposed for the south-eastern coast of the U.K. (Pethick, 1993) and for the Mississippi delta (Day & Templet, 1989; Day *et al*., 1997).

Predicting long-term marsh elevation response to relative sea-level rise

The accurate determination of the ability of any particular coastal wetland to survive sea-level rise is crucial if appropriate management actions are to be taken to ensure its survival. For many years, vertical accretion was used as a measure of the vertical growth of a wetland surface (e.g. Baumann *et al*., 1984; Stevenson *et al*., 1985; Reed & Cahoon, 1993). Vertical accretion was compared directly to local rates of RSLR and if accretion was less than RSLR, then an ‘ accretion deficit ’ existed and the wetland would submerge. As indicated in the Introduction, however, accretion alone is insufficient to determine if a wetland is growing vertically at a rate sufficient to offset water-level rise. Cahoon *et al*. (1995*b*) showed that the rate of soil elevation change must also be measured because of shallow subsidence occurring in the upper soil profile. Soil elevation change measurements allow a short-term comparison of the change of a wetland surface relative to water level changes but, alone, are insufficient to determine long-term survival.

As emphasized earlier, short-term field measurements do not fully integrate long term processes, such as compaction and decomposition, that affect wetland elevation and do not take into account possible elevation feedback mechanisms. Specifically, changes in soil elevation can result in changes in sediment deposition, decomposition and primary production. Therefore, it is believed that the accurate prediction of whether a coastal wetland will survive requires both field measurements of accretion and soil elevation change and modelling, which takes into account these long term processes and elevation feedback mechanisms.

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