

12 Coastal Wetland Vulnerability to Relative Sea-Level Rise: Wetland Elevation Trends and Process Controls

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12.1 Introduction

The distribution of tidal saline wetlands (e.g., salt marshes and mangroves) is increasingly impacted by global environmental change, including human alteration of the world's coasts and sea-level rise (Kennedy et al. 2002; Poff et al. 2002). Rates of salt marsh and mangrove loss appear to be accelerating (Nicholls et al. 1999). A better understanding of wetland accretionary dynamics, controls and constraints, and in particular responses to sea-level rise is required to inform the maintenance and restoration of these systems. Differences in wetland form and function result from a range of continental- and regional-scale processes (Mitsch and Gosselink 2000). Local geomorphology, climate regime, and hydrology result in differences in sediment supply, primary production and decomposition, subsidence, and autocompaction, resulting in variations in elevation among both salt marsh and mangrove sites. Combinations of these controls mean that individual wetland sites show different degrees of vulnerability to current and near-future environmental change.

Several vulnerability assessment approaches have been developed during the past two decades, including the Global Vulnerability Assessment, first developed by Hoozemans et al. (1993) and recently refined in DINAS_COAST (McFadden et al. 2003), and the Coastal Vulnerability Index (Gornitz 1991; Hammar-Klose and Thieler 2001). These approaches offer valuable planning tools for coastal resource managers at the broad (i.e., global, continental, macro-regional) scale as they allow the identification of both patterns of relative vulnerability and vulnerability 'hotspots'. However, the numerical scores that they produce cannot be easily assigned a precise physical meaning and

they suffer from downscaling problems, yielding predictions that are not always correct at the local scale. A more thorough understanding of coastal wetland vulnerability requires data from specific wetland sites on not only the physical and biotic parameters described above, but also: (1) the relationship among sedimentation, organic soil formation, vertical accretion, and surface elevation change and (2) the interaction of these processes, themselves subject to considerable spatial and temporal variability, with local relative sea-level rise (Day et al. 1999; Fig. 12.1).

To provide site-specific information on these key processes and interactions, the Surface Elevation Table–Marker Horizon method was developed for use in marshes (Cahoon et al. 1995) and shallow water environments (Cahoon et al. 2000a, b). The method incorporates simultaneous measurements of wetland elevation from a surface elevation table (SET; Boumans and Day 1993; Cahoon et al. 2002a, b) and vertical accretion from artificial soil marker horizons (MH; e.g., Cahoon and Turner 1989). The SET-MH methodology allows determination of not only the current accretion and elevation trajectories of the wetland relative to local sea-level rise, but also the influence of subsurface processes on elevation change. The latter has been termed ‘shallow subsi-

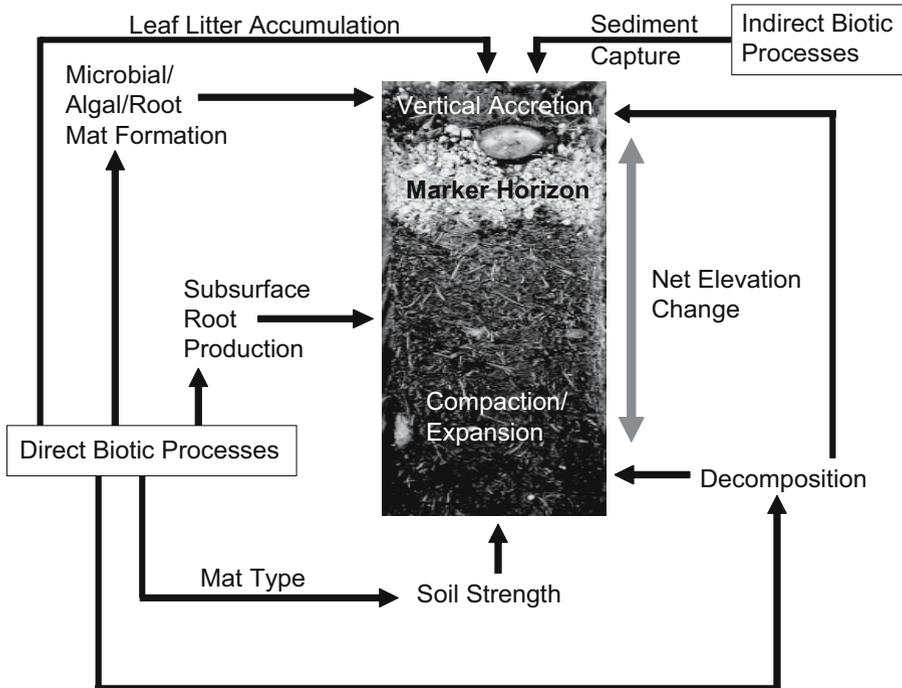


Fig. 12.1 Diagram showing direct and indirect biotic controls on vertical accretion and elevation change

dence' (Cahoon et al. 1995) to distinguish it from long-term, deep subsidence on a geological scale.

An informal network of SET-MH monitoring stations was developed during the past 15 years as 65 scientists from 18 countries applied this approach in nearly 200 coastal wetland settings. The stations are concentrated in Europe, North America, the Caribbean, and western Pacific. A few data records are now >10 years duration. The informal SET-MH network, and associated measurements (e.g., RSLR, tidal range, soil properties), provides a nascent global network of elevation and accretion monitoring stations using a common methodology that spans a range of coastal wetland types and settings. This methodology allows a quantitative comparative assessment of wetland response to current sea-level rise across sites and begins to identify the key processes that control the rate and style of wetland submergence or survival. Although this paper focuses on near-term responses to sea-level rise, this network database also provides site-specific data required for modelling longer-term elevation trajectories (e.g., Day et al. 1999; Rybczyk and Cahoon 2002), where feedbacks occurring on varying timescales influence wetland elevation change (e.g., relative elevation, productivity, sedimentation).

In this paper, we describe biotic and hydrologic controls on coastal wetland elevation dynamics. Specifically, we review the limited amount of literature that directly compares measures of hydrologic and biotic processes with direct measures of wetland elevation change. In addition, we present a first and preliminary analysis of near-term trajectories of the global SET-MH data set in order to improve our understanding of salt marsh and mangrove responses to current sea-level rise and to identify critical factors and processes controlling coastal wetland elevation dynamics across a diversity of wetland settings.

12.2 Biotic Process Controls

Habitat stability of coastal wetlands in relation to sea-level rise is dependent on a feedback relationship between hydro-edaphic conditions and the biotic community that characterizes the ecosystem (Fig. 12.1). Within certain environmental bounds, as yet not well defined, the feedback relationship between biotic and abiotic components allows the wetland to self-adjust to prevailing water levels and, consequently, to keep pace with rising sea-level (Stevenson et al. 1986; Nyman et al. 1993, 1995). Although organic matter accumulation and the processes controlling it are widely recognized and well studied in some wetland habitats, little empirical information exists directly linking biotic processes to vertical accretion and surface elevation change, despite wide recognition that biotic contributions to soil elevation may vary from low (mineral) through intermediate (organic) to very high (peat).

A review of soil organic matter dynamics is beyond the scope of this paper. Instead, this section describes several biotic processes potentially contributing to elevation change and provides data linking these processes where they exist. Biotic processes can be divided into two categories: (1) indirect, which modify mineral deposition or erosion, and (2) direct, which directly alter soil volume and/or soil strength and resistance to erosion or compaction.

12.2.1 Indirect Biotic Processes

A number of studies have demonstrated the effects of vegetation on sediment deposition (e.g., Gleason et al. 1979; Leonard et al. 1995; Furukawa et al. 1997; Rooth et al. 2003). The shoots or aerial roots of wetland plants can baffle flows (Furukawa et al. 1997; Leonard and Reed 2002; Morris et al. 2002), which may increase rates of sediment deposition. The presence of wrack or plant litter on the soil surface may also trap mineral sediment, thus contributing to vertical accretion. In a manipulative experiment in which the amount of *Phragmites australis* litter was varied from 250 g DW m⁻² to 2000 g DW m⁻², the amount of trapped sediment increased exponentially (Rooth et al. 2003). The combined effect of reducing flows and stabilising the substrate may lead to a positive relationship between vegetative aboveground biomass and marsh elevation change, although few studies have shown this link experimentally. Morris et al. (2002), for example, found that nutrient enrichment increased production and standing biomass of salt marsh plants, which accelerated elevation gain by increased sediment trapping from 5.1 mm year⁻¹ to 7.1 mm year⁻¹. In a study of the effects of mangrove aerial roots on mineral sedimentation, Krauss et al. (2003) found that elevation change rates varied with root type from -0.2 mm year⁻¹ to 3.4 mm year⁻¹.

12.2.2 Direct Biotic Processes

Although mineral sedimentation may be affected by vegetation characteristics, biotic processes that contribute directly to soil volume have the greatest potential to influence vertical accretion and elevation change. These biological processes can be divided into surface and subsurface processes. Surface processes include the accumulation of decaying organic matter such as leaf litter, or the formation of living benthic mats (e.g., microbial, algal, root), which contribute to vertical accretion and also influence the resistance of the deposit to compaction or erosion. Subsurface processes such as root production, root mortality, and decomposition influence soil volume, contributing either to expansion or to subsidence.

Litter Deposits

The relative contribution of plant litter deposition to vertical accretion and elevation change in coastal wetlands likely varies spatially and temporally. However, data linking these processes is limited. We examined vertical accretion and leaf litter standing stocks in mangrove forests where the accumulation of litter varies depending upon aboveground production, consumption by detritivores, microbial decomposition, and tidal flushing (McKee and Faulkner 2000; Middleton and McKee 2001). Basin mangrove forests can accumulate thick deposits of leaf litter that contribute to vertical accretion. For example, vertical accretion rates measured in a basin forest in Southwest Florida were positively related to litter standing stocks (Fig. 12.2A). These types of forests occur in depressional areas where tidal action is less than

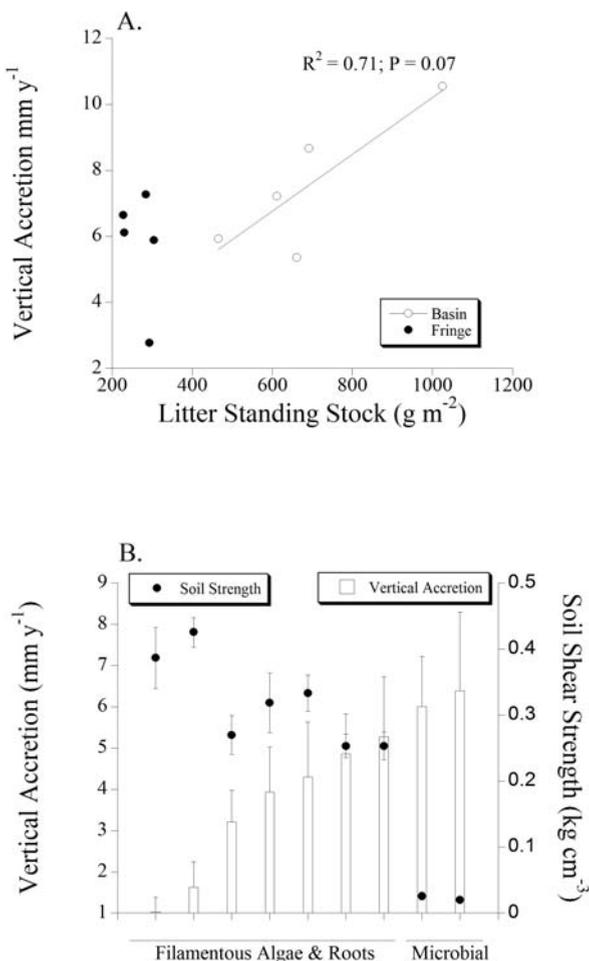


Fig. 12.2 Surface biotic processes directly contributing to vertical accretion in mangrove forests. **A** Litter accumulation is significantly correlated with vertical accretion in basin forests, but not in fringe forests where tidal action and other factors prevent it. **B** Variation in vertical accretion rates of benthic mats (above mesh screens pinned to the soil surface) composed of turf algae/mangrove roots and microbial communities in relation to their shear strength

along exposed shorelines, but where the soil and litter layer typically remain saturated, slowing decomposition. Over time, many layers of decaying leaves accumulate on the forest floor. In comparison, less litter accumulates in fringe forests with more frequent tidal flushing and faster degradation rates. In fringe forests, no relationship was found between accumulated litter and vertical accretion (Fig. 12.2A). Further work is needed to determine how these differences in litter deposition influence elevation change in mangrove forests and if surface accumulations of litter are important in maintaining elevations in other wetland types.

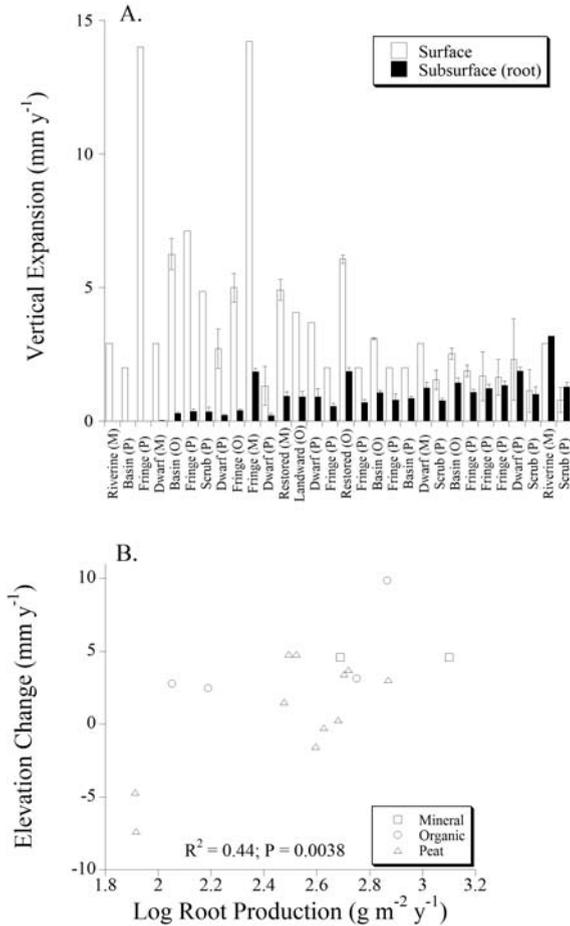
Benthic Algal/Microbial/Root Mats

Benthic mats composed of filamentous algae, roots of emergent plants, microbial communities, or a combination of these may form on the soil surface of coastal wetlands. For example, turf algae may form thick, living mats in red mangrove (*Rhizophora mangle*) forests and have been observed throughout the Caribbean Region (e.g., Florida, Belize, Honduras, Panama; McKee, personal communication). Another type of benthic mat is formed by growth of microbial communities consisting of cyanobacteria (Cyanophyta), diatoms (Chrysophyta), and other microorganisms (Joye and Lee 2004). Rates of vertical mat growth, which were determined on screens (1 mm mesh) pinned to the soil surface in a mangrove forest in Belize (Fig. 12.3B), varied from 1 mm year⁻¹ along the shoreline (turf algal mats) to 6 mm year⁻¹ in interior dwarf mangrove stands (microbial mats). The slower growing mats composed of filamentous algae and mangrove roots had high shear strength, whereas the microbial mats had almost no resistance to shearing (Fig. 12.3B). Variation in vertical accretion and shear strength of these benthic mats is intriguing and suggests a potential role in elevation change. Microbial mats have also been observed in some salt marshes where they form mounds of 10 cm or more in thickness (S. Joye, personal communication.). Further investigation is required, however, to determine whether benthic mats can influence elevation change in these and other coastal wetlands.

Subsurface Root Production

Accumulation of soil organic matter occurs when production exceeds decomposition rates. In coastal wetlands, slow decomposition, particularly of plant roots, occurs under the predominately anaerobic conditions in flooded soils. Thus, variation in root production may be the primary influence on elevation change through root inputs to soil volume. For example, reductions in soil organic matter accumulation following mass plant mortality (i.e., lack of root input) can lead to elevation declines through peat collapse (Cahoon et al. 2003, 2004). Despite general recognition of these relationships, supported by modelling studies, no direct measure of root contributions (or losses through decomposition) to elevation change have previously been

Fig. 12.3 A Comparison of surface (deposition above a marker horizon) and sub-surface (root production) contributions to vertical soil expansion across different mangrove forest types and soils (*M* mineral, *O* organic, *P* peat). Root volume produced ($\text{cm}^3 \text{m}^{-2} \text{year}^{-1}$) was calculated from root production rates using an average root density of 1.1 g cm^{-3} . Values are the mean and SE of one to nine replicate plots. **B** Relationship between root production rates (in-growth bags) and elevation change (SET) measured in 18 mangrove forests in different geographic locations and three soil types (mineral, organic, peat). Values are the mean and SE of one to nine replicate plots



made in coastal wetlands. We consequently assessed subsurface contributions of root volume to vertical change in comparison with measured vertical accretion rates to examine surface versus subsurface inputs to soil volume. In addition, we examined the relationship between root production and elevation change.

Data on root production and vertical accretion were collected from 30 mangrove sites; surface elevation change was also measured at 18 of these sites, although the length of the records differed. Contribution of root volume to vertical expansion was calculated by converting mass to volume using mangrove root density (g cm^{-3}) determined with a pycnometer. The relative contribution of root volume to subsurface expansion is compared to surface vertical accretion in Fig. 12.3A. Depending on the site characteristics, root contribution to vertical expansion varied from 0 mm year^{-1} to 3 mm year^{-1} , indicating a potentially substantial effect on elevation in some

locations. For those sites (undisturbed only) instrumented with SETs, there was a significant correlation between elevation change and root production (Fig. 12.3B).

The relative importance of biotic processes in the sustainability of coastal wetlands obviously depends upon the physical setting and their role relative to that of abiotic factors in marsh vertical development. In this section, we provide a few examples in which biotic processes influence soil elevation change by contributing directly or indirectly to vertical accretion and/or soil volume. However, additional studies are needed to fully evaluate the role of biotic processes in maintaining soil elevations relative to sea-level in coastal wetlands.

12.3 Hydrologic Process Controls

There is an extensive literature on wetland hydrology and its indirect influence on wetland elevation by: (1) delivery of suspended sediments to wetland surfaces and (2) regulation of plant growth, decomposition, and soil organic matter accumulation through control of the soil oxidative state. However, data on the direct relationship between water flux/storage and wetland elevation change is limited. In this section, we review the literature on the direct effects of hydrology on wetland elevation by the processes of compression and dilation storage (e.g., shrink–swell).

There are two mechanisms of water storage in wetland soils. Saturation storage is associated with the displacement of gases from pore spaces by water and is limited to the sediment above the water table where pressures in the ‘free’ (e.g., unbound) water are low enough to allow atmospheric gases to enter the sediment (Nuttle et al. 1990). Dilation storage is associated with changes in the bulk volume of the sediment and can occur throughout the sediment. As more water is incorporated into the sediment below the water table, the sediment must dilate (e.g., swelling clays) and the sediment volume change is equal to the volume of water added to storage (Nuttle et al. 1990). This water storage mechanism displaces the wetland surface. Evidence for the mechanics of dilation storage in wetland sediments can be found in the high degree of compression under a load and the significant shrinkage when dried. The amount of dilation storage and degree of surface displacement will vary with soil type (i.e., organic vs mineral). It is important to understand such water-storage controls on wetland elevation in order to properly evaluate sources of variation in long-term elevation trends. The role of wetland hydrology should be considered both at the surface and within the subsurface.

12.3.1 Surface Wetland Hydrology

As a result of surface topography, water floods a marsh to different depths, resulting in larger vertical loading in areas of deeper flooding. Tidal flooding of 10 cm depth is sufficient to deform a salt marsh surface by both compression and lateral movement, resulting in uplift (Nuttie et al. 1990). Storm tides, which can be several meters deep, can also deform the salt marsh surface (Cahoon 2003). The storm surge from Hurricane Andrew compressed the surface of a rapidly deteriorating salt marsh in Louisiana by 33 mm (Cahoon et al. 1995) and the deformed marsh surface had not rebounded 8 years later (Rybczyk and Cahoon 2002). In North Carolina, the surface of a salt marsh with 60 % soil organic matter content was compressed by 5–6 mm after each of two storms to strike the marsh in consecutive years. The deformed surface rebounded >10 mm the following year, only to be compressed 20 mm by another storm (Cahoon 2003). At these sites, the influence of water table fluctuations, organic substrates, and pre-existing marsh deterioration all appear to have influenced the compression of the substrate. However, the mechanism driving the potential rebound of such deformed surfaces is not known.

12.3.2 Subsurface Wetland Hydrology

Infiltration during flooding by astronomical tides can cause shrink–swell of the marsh substrate by dilation storage (Harrison 1975; Nuttie and Hemond 1988; Nuttie et al. 1990), although tidal flooding does not cause shrink–swell in all marshes (Cahoon et al. 1995). In addition, given that the tidal effects in some marshes decline exponentially with distance from the creek bank (Nuttie 1988), loss of water through evapotranspiration (ET) by vegetation can become an important control on water storage in interior portions of the marsh. Indeed, up to 3.0 mm of diurnal variation in surface elevation was related to ET in salt and brackish marshes in the Bay of Fundy (Paquette et al. 2004) and a salt marsh in Louisiana (Perez et al. 2003; Fig. 12.4).

Longer-term trends (e.g., weekly to seasonal) in groundwater levels can influence wetland surface elevation. Incremental changes in ground water level explained 40 % of the variation in incremental surface elevation change in mangrove forests along the Shark River in Everglades National Park (Smith and Cahoon 2003), with surface elevation greatest during the wet season. Similarly, lowering of the marsh water table by drought resulted in a decrease in surface elevation in marshes in east Texas (10–15 mm; Perez and Cahoon 2004), in south Louisiana (20 mm; Perez et al. 2003; Swarzenski et al. 2006; Fig. 12.4), and in southeast Australia (Rogers et al. 2005).

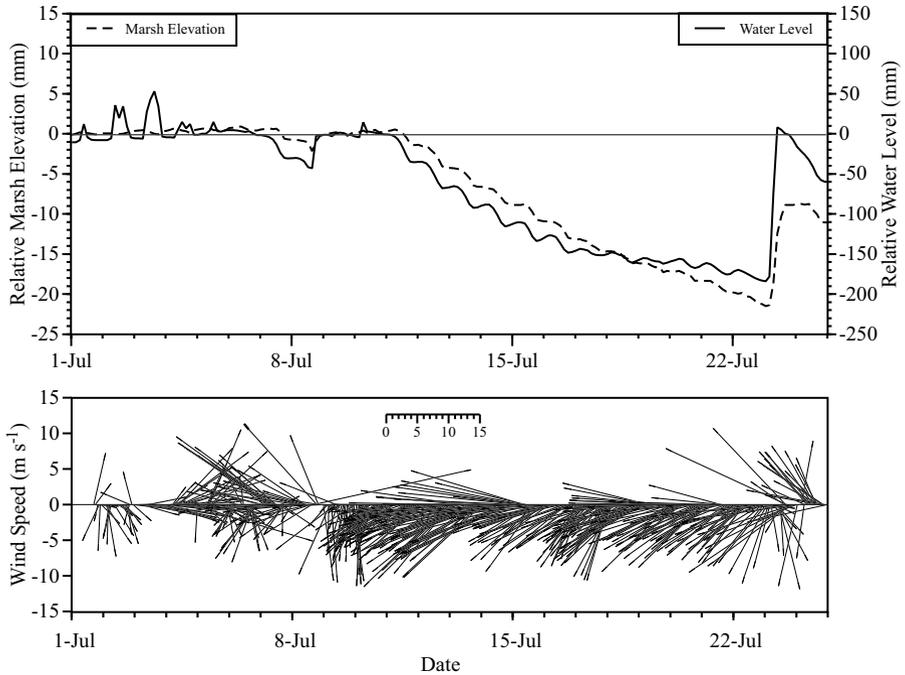


Fig. 12.4 *Top* Change in relative marsh elevation and marsh water level during a two-week wind-driven water-level drawdown event (note difference in scales). *Bottom* Wind speed and direction during the two-week period. Source: Perez et al. (2003)

12.4 Findings from the SET Network

The combination of biotic and hydrologic processes described above, acting at different rates and over different timescales in the wide array of wetland types and settings, exerts an aggregate influence on surface elevation change. The SET-MH approach can provide site-specific information on elevation trends, the degree of subsurface influence on elevation; and when used in combination with process measures, the relative contribution of different processes to elevation change. In this section, we present the first and preliminary analysis of the SET-MH monitoring network.

12.4.1 Data Analysis

Linear accretion and elevation trajectory estimates were made for each wetland setting. Shallow subsidence was calculated as the difference between the

linear accretion and elevation trajectories (Cahoon et al. 1995). Average trajectories were compared to relative sea-level rise (RSLR) and *t*-tests were used to test for significant difference. A simple linear regression was used to test for associations between accretion and elevation change trajectories and RSLR, tide range, soil bulk density, and soil organic matter.

Temporal and spatial scaling constraints influence data analysis and interpretations. The present analysis compares short-term accretion and SET measurements to longer-term, historical records of sea-level rise. Further difficulties arise where sea-level records are gathered from tide gauges at some distance from, and in different geotectonic settings to, the wetland of interest. It is also difficult to relate individual site behavior to more regional trends in sea-level change and marsh morphological change. These data constraints limit the direct comparison by site. Nevertheless, it is still possible to establish a broad-based assessment of relationships between aspects of marsh sedimentation, elevation change and sea-level change. The SET network provides a starting point from which questions of wetland vulnerability and sustainability can be assessed. The data analysis is presented for salt marshes and mangroves separately because of their distinct vegetation structures. Furthermore, salt marsh and mangrove settings occupy different climatological (i.e., latitudinal) regions, although in some locales they can co-exist (e.g., south-eastern Australia).

Since both salt marsh and mangrove systems influence and are influenced by the dominant biogeomorphic processes occurring within the coastal zone, trends in accretion and elevation change are analyzed according to geomorphic settings. Of the many classification schemes available, the one developed by Woodroffe (2002) was chosen as the starting point for this analysis because it applies to both salt marsh and mangrove systems and builds on many previous classifications. The geomorphic classes include: back-barrier, embayment, estuarine, deltaic, open coast, and drowned valley. We added 'oceanic islands' as an additional class to more adequately reflect the geographic diversity of the network sites. Settings such as Twin Cays (Belize), Roatan (Honduras), and several islands of the Federated States of Micronesia fit into this class. We further adapted the classification by including our drowned valley sites (located only in Australia) in the estuarine class because Roy et al. (2001) included drowned river valleys of Australia in the estuarine class. Thus, our analyses included the following classes: back-barrier, embayment, estuarine (including drowned valley), deltaic, open coast, and oceanic island. Although salt marsh and mangrove data in the network are distributed across these classes differently (e.g., oceanic islands are only represented by mangrove settings, and deltas are only represented by salt marshes), this classification scheme, modelled after Woodroffe (2002), is a useful way of examining salt marsh and mangrove data on a global scale.

12.4.2 The Salt Marsh SET Network

The SET salt marsh network comprises 65 geographical locations and 108 coastal wetland settings in North America, Europe and Australia. The 'sample network' reported here, where data availability is of sufficient quality for analytical purposes, covers 34 of these locations and 78 wetland settings. As expected in a developing methodology, short record lengths predominate; one-third of all records are less than three years in length and two-thirds are of less than five years' duration. The analytical problems caused by short record lengths are discussed further below.

Four geomorphic classes are represented in the salt marsh dataset (back-barrier, coastal bay, deltaic, estuarine) from seven main geographic regions: NE North America, SE North America, Northern Gulf of Mexico, SW United States (Pacific), SE Australia, NW Europe, and Northern Mediterranean. Unlike the Mediterranean, NW Europe is geologically stable and has a legacy of sediment supply, sea-level history, and coastal configurations strongly influenced by the Pleistocene glaciations. NW Europe is meso- to macro-tidal, and much reduced contemporary sediment supply from early Holocene levels and extensive reclamation in historical times has meant that many remaining marsh areas still show high rates of areal loss and internal marsh break-up (Carpenter and Pye 1996). The Mediterranean is geologically active and micro-tidal, with river processes in combination with wave-driven processes producing barriers to coastal lagoons and their associated wetlands. Historically, these systems have been sustained by episodic forcings, which have injected pulses of sediment onto wetland surfaces. However, coastal retreat, saltwater intrusions, and reductions in riverine sediment supply (e.g., disconnection of river channels from delta plains) have led to low accretion rates and poor vegetation productivity in many Mediterranean deltas (e.g. Rhone: Pont et al. 2002; Ebro: Curco et al. 2002; Po/Venice lagoon: Abrami and Day 2003; Day et al. 1999).

The Atlantic shoreline of eastern North America is 80–90% estuaries and lagoons. The northeast coast has undergone cycles of glaciation, is meso- to macrotidal and has a moderate to high sediment supply. The southeastern coast is characterized by extensive barrier islands, lagoons, and drowned river valley estuaries. Two main geomorphic settings present in our sample from both the northeast and southeast coasts are back-barrier and coastal bay marshes. The northern Gulf of Mexico shoreline is 80–90% estuaries and lagoons dominated by micro-tidal settings, including the Mississippi River delta, which is characterized by high rates of subsidence and historically high sedimentation rates. Much of the recent sediment load of the Mississippi River is currently deposited on the continental slope and is thus not available to coastal marshes. The Pacific coast of the United States is geologically active, has a narrow continental shelf, and has a limited extent of mesotidal coastal marshes (10–20%). In the meso-tidal, swell wave environment of SE Aus-

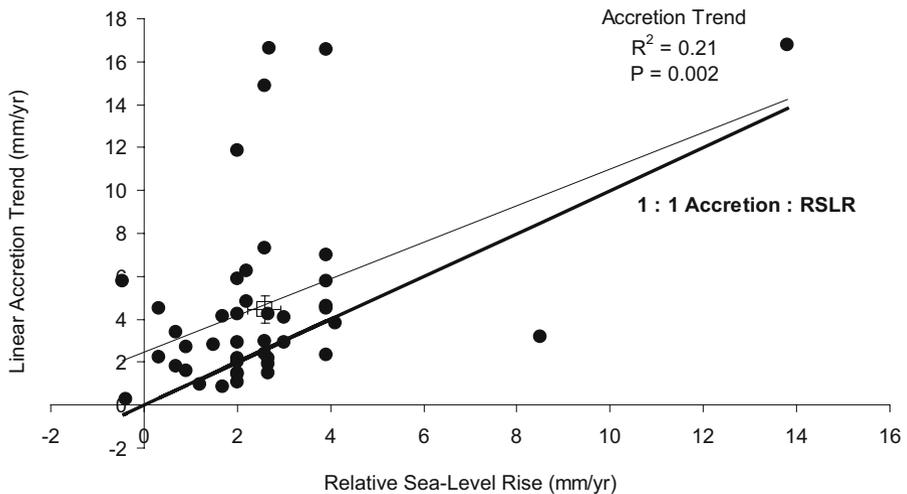
tralia, wetlands are associated with low-energy locations in bays and gulfs, in estuaries, and between barriers on multiple barrier coastlines.

Results

Average accretion rates were greater than corresponding rates of RSLR ($P < 0.001$), and accretion rates showed a significant positive linear relationship to RSLR ($P = 0.002$; Fig. 12.5). Average elevation rates were also greater than RSLR, ($P = 0.06$), but no linear trend was evident between elevation and RSLR rates ($P = 0.20$). The close correspondence between rates of surface accretion and sea-level rise suggests that, in general, salt marsh surface processes are exhibiting ‘keep up’ behavior as the sea level rises.

The four sites in Fig. 12.5 with strong accretionary responses are characterized by high sediment supply. The one site that lags behind sea-level rise for both accretion and surface elevation change is Old Oyster Bayou, a *Spartina alterniflora* marsh in a rapidly subsiding part of the Mississippi River delta. Although a riverine sediment source is nearby, the severely altered local hydrology apparently limits sedimentation such that vertical accretion and elevation change are essentially insignificant except during hurricane storm events (Rybczyk and Cahoon 2002). Model results indicate that this marsh will become submerged within the next 30 years because of deep subsidence rates, even if there is a 12-year return frequency for major hurricanes (Rybczyk and Cahoon 2002).

Average elevation rates were significantly less than accretion rates ($P < 0.001$), indicating that shallow subsidence occurs at many sites. However,



the variability is large, suggesting that the local process environment exerts a strong influence. Disaggregated by geomorphic setting, deltas are characterized by high accretion with only moderate elevation change (Fig. 12.6), resulting in high shallow subsidence ($P=0.03$). Embayments also showed high shallow subsidence, but at a lower average accretion rate ($P=0.03$). Back-barriers and estuaries generally have good concordance between accretion and elevation change. In terms of geographic region (Fig. 12.7), the United States Atlantic NE and Mediterranean Europe are characterized by high accretion and high elevation change. The Mediterranean estimates are high because the network sites are located in areas receiving riverine sediments (e.g., deltas). Previously published evidence from eastern England (Cahoon et al. 2000a) suggests that many NW European sites are likely to show similar patterns of behavior. The United States Atlantic SE and Gulf Coast are characterized by high accretion and low elevation change, the United States Pacific and Australian sites by low accretion and low elevation change. Lastly, there are no

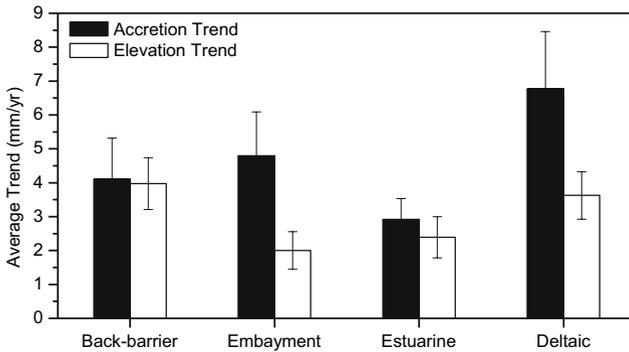


Fig. 12.6 Trends in accretion and elevation for 49 salt marsh sites in the SET network, disaggregated by geomorphic setting

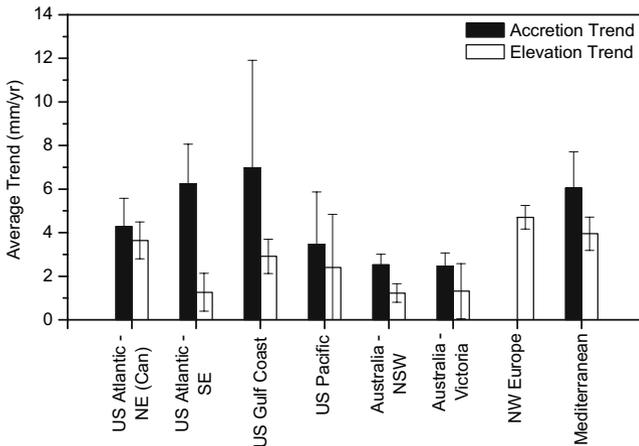


Fig. 12.7 Trends in accretion and elevation for 49 salt marsh sites in the SET network, disaggregated by geographic region

clear trends in the relations between either accretion or elevation change and tidal range in relation to geomorphic setting ($P>0.1$).

12.4.3 The Mangrove Forest SET Network

The SET mangrove network comprises 25 geographical locations and 72 coastal wetland settings in the Gulf of Mexico, the Caribbean, Central America, the Western Pacific, and Australia. Data analysis was conducted on 60 mangrove forest settings from 19 of the sites where sediment accretion and elevation change records were >1 year. Approximately one-half of the data records span 4 years or less.

Five geomorphic classes (adapted from Woodroffe 2002) are represented (back-barrier, embayment, estuarine, open coast, oceanic island), from five main geographic regions (Gulf of Mexico, Caribbean, Pacific Central America, SE Australia, Micronesia), and seven countries (United States, Mexico, Belize, Honduras, Costa Rica, the Federated States of Micronesia, Australia). The small oceanic islands in the Caribbean are microtidal, remote from terrigenous sediment input, experience only moderate rates of RSLR, and rely mostly on biogenic processes for elevation maintenance (Cahoon et al. 2003). The Micronesian islands are also remote from terrigenous influence, but have very high topography and rainfall, resulting in somewhat less dependence on biogenic processes. The mangrove settings from the Florida border of the Gulf of Mexico are classified as embayments, open coast, and estuarine. However, these settings are somewhat similar to the Caribbean islands in terms of tidal regime, sediment input, mangrove species composition, and local RSLR. The SE Australian coastline experiences a meso to macro-tidal regime; chosen settings are low-energy, such as bays, back-barriers, and riverine habitats. The geologically active Pacific coast of Central America features large, macrotidal estuaries with high sediment loads. The settings chosen in Costa Rica are experiencing substantial subsidence (Emery and Aubrey 1991). This wide diversity of habitats and environmental settings presents a first opportunity to study processes and vulnerabilities on a global scale.

Results

Accretion rates exceeded sea-level rise ($P=0.03$, $n=41$) and increased with increasing rates of sea-level rise ($P<0.0001$, $n=41$) across the network of settings. However, this accretion surplus did not necessarily translate into elevation gain, as most sites had elevation deficits with respect to RSLR ($P<0.001$, $n=55$). No linear trends were evident between elevation change rates and RSLR ($P=0.49$, $n=55$). The discrepancy between accretion and elevation change resulted in an overall significant positive shallow subsidence ($P=0.017$, $n=41$). Accretion also showed a significant positive relationship to

tidal range ($P=0.084$, $n=38$). Estuarine settings showed a strong linear relationship between accretion and RSLR (Fig. 12.8; $P<0.001$, $n=20$), as did embayments, although the fit was less significant ($P=0.08$, $n=8$). Embayments were the only class showing increasing elevation change rates with increasing RSLR ($P=0.07$, $n=8$) and tidal range ($P=0.07$, $n=8$) and increasing accretion with increasing tidal range ($P=0.08$, $n=8$). These results suggest there exist belowground process controls on mangrove surface elevation dynamics.

No strong vegetation-dependent accretion/elevation trends were evident at a global scale from the network. *Avicennia* and *Rhizophora* provinces displayed similar trends with respect to sea-level rise and tidal range. The significantly positive relationship between accretion and soil bulk density ($P=0.054$, $n=10$), and the negative logarithmic relationship between accretion and percent organic matter ($P=0.003$, $n=12$) were both related to differences among geomorphic classes. Peat-based soils of the oceanic islands (Belize, Roatan) had the lowest bulk density, highest organic matter content, and the lowest accretion. Mineral, riverine Pacific Central American mangrove soils had the highest bulk density, lowest organic content, and the highest accretion. Here too, elevation failed to show any relationships to bulk density or organic content, suggesting belowground process controls on elevation dynamics.

Shallow subsidence was seen in many of the 41 settings for which data were available, yet no shared characteristics suggested a unifying mechanism. Subsidence was greatest in areas that received highest sedimentation: settings on

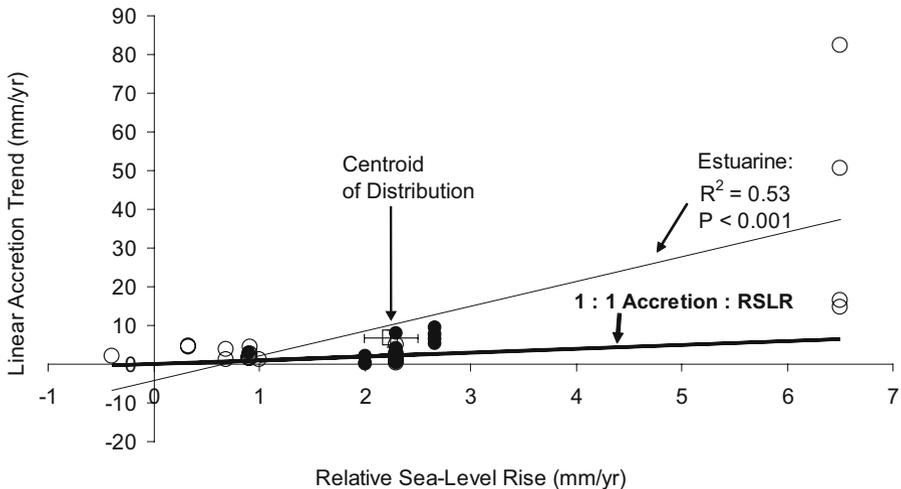


Fig. 12.8 Linear trend in accretion versus relative sea-level rise for mangrove sites in the SET network. The *heavy black line* represents the 1:1 relationship. The *thin black line* represents the slope for riverine mangroves. The *open box* with two-dimensional error bars represents the centroids of the distribution

the Pacific coast of Costa Rica accreted vertically at a rate of 41 mm year⁻¹, yet elevation increased at a mere 1 mm year⁻¹. This large difference is likely due to the compaction and decomposition of recent deposits.

The consistent elevation gain of Caribbean mangroves despite low sediment accretion underscores the importance of organic belowground productivity in these settings. Caribbean islands in particular had elevation 50% greater than accretion. This relationship is not specific to particular mangrove species, since the Caribbean islands share the same species as many of the other settings. Rather, the contribution of root growth may be related to nutrient status, hydrology, decomposition rates, disturbance regimes, and other site-specific variables.

Groundwater is known to directly influence mangrove surface elevation by altering soil volume (Smith and Cahoon 2003; Whelan et al. 2005). The sampling period throughout southeastern Australia (2000–2004) occurred during an intense El Niño-related drought. Associated negative SOI and rainfall reductions caused significant subsidence and lowered rates of surface elevation gain at settings in southeastern Australia. This may explain the low rate of surface elevation gain in these settings compared to the global network. While sea levels may be locally reduced under drought conditions, repeated drought cycles have the potential to significantly affect the structure and function of mangrove forests (Drexler and Ewel 2001).

12.5 Further Considerations

This review of the processes controlling marsh surface elevation change shows that biotic processes, both directly and indirectly, are likely to have a major influence on marsh vulnerability to future sea-level rise. The influence of biotic processes will vary depending upon: sediment supply, hydrology, dominant vegetation, and plant community structure. In addition, it seems clear that variations in tide, ET, and river discharge can influence surface elevation of some of the more organic wetland substrates over short time-scales. Empirical measures of the influence of tidal flooding and groundwater fluxes on wetland surface elevation are available from a limited number of wetlands encompassing a limited range of geomorphic settings and soil types. The responses of a wider range of wetlands to variations in soil water storage need to be determined to elucidate the importance of this driver of elevation change.

Interpreting the status of coastal wetlands across the range of geomorphic settings and localities encompassed by the SET network has identified several significant relationships among accretion, elevation change, and hydrologic drivers (e.g., tidal range, RSLR). Elevation change and accretion in wetlands where the delivery of sediment to the marsh was supported by local sediment

supply and tidal/estuarine hydrology generally were seen to keep pace with RSLR. However, examining the data sets as a whole masks some important differences. For example, salt marshes are typically found at much higher intertidal levels in NW Europe than on the eastern seaboard of the United States. Furthermore, for minerogenic marshes, accretion rates and rates of surface elevation change decline over time as surfaces become progressively higher in the tidal frame. The nature of this decline over decadal to centennial timescales is strongly asymptotic towards Highest Astronomical Tide, although reaching an equilibrium level below this height (French 1993; Allen 2000). Such behavior complicates the assessment of marsh performance/sea-level relations across such varied sites. Whereas 'mature' marsh surfaces will exhibit an equilibrium level related to tidal parameters and thus respond to changes in sea level and frequency of tidal inundation, 'immature' marshes will show high, non-equilibrium rates of accretion and surface change as they build up rapidly from low positions in the tidal frame.

Importantly, examination of elevation change and accretion data available in the SET network has demonstrated the importance of time scale considerations both in data collection and interpretation. Due to the effects of local hydrology measurements of surface elevation for a given marsh should always be collected at the same stage of the tide, meteorological conditions, or season of the year to minimize bias in the data. Interpretations of elevation trajectories should be based on multi-year data records so as to incorporate as much temporal variability as possible but there is also the issue of the record length necessary to allow meaningful comparison with the sea-level record. To assess the long-term vulnerability of coastal wetlands, studies must incorporate the range of variability in biotic and abiotic surface and subsurface processes within the wetlands reviewed in this paper as well as both cyclic and episodic changes in local sea level.

The data available in the SET network can be used to predict the future vulnerability of coastal wetlands when used to drive numerical models that consider more than just future changes in sea level. How will predicted changes in surface runoff and groundwater, local sediment delivery to the coast, and coastal storm intensity interact with predicted accelerations in sea-level rise to affect wetland elevation change? Will a long-term reduction in groundwater flow result in a persistent reduction in wetland elevation that will exacerbate the effects of sea-level rise? How will changes in plant productivity and latitudinal shifts in vegetative communities with global change affect the role of biotic processes in wetland soil development? As well as future changes in climate drivers, some of the processes currently maintaining wetland elevation may not be sustainable in the long-term and over large areas. Thus, for example, marsh edge erosion may feed sediment onto adjacent surfaces. Whilst such processes may lead to local accretion and surface height gains locally, they may in fact be symptomatic of more long-term, regional patterns of marsh retreat and net loss of area.

This first analysis of accretion and elevation change data from the SET network has raised many questions. Future work should seek a better understanding of the relationships between abiotic and biotic factors in different coastal systems and how the combination of these factors results in characteristic trajectories of surface elevation change. Studies that focus on effects of specific factors such as nutrients, temperature, elevated CO₂, and flooding regimes, as well as their interactions, are needed to quantify and predict future wetland elevation change. Such studies should be coupled with a detailed interrogation of the existing database and a strategic extension of the SET-monitoring network to embrace regions and geomorphic settings as yet unsampled. The ultimate goal is to provide a wider understanding of the processes determining wetland vulnerability and sustainability worldwide.

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