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Groundwater Control of Mangrove Surface Elevation: Shrink and Swell Varies with Soil Depth

Kevin R. T. Whelan[1,*], Thomas J. Smith III[2], Donald R. Cahoon[3], James C. Lynch[3], and Gordon H. Anderson[4]

[1] *U.S. Geological Survey, Florida Integrated Science Center, c/o Florida International University, Department of Biological Sciences, Owa Ehan. 167, University Park, 11200 SW 8 Street, Miami, Florida 33199*

[2] *U.S. Geological Survey, Florida Integrated Science Center, 600 Fourth Street South, St. Petersburg, Florida 33701*

[3] *U.S. Geological Survey, Patuxent Wildlife Research Center, 10300 Baltimore Avenue, BARC–EAST Building #308, Beltsville, Maryland 20705*

[4] *U.S. Geological Survey, Florida Integrated Science Center, c/o Everglades National Park Field Station, 40001 State Road 9336, Homestead, Florida 33034*

ABSTRACT: We measured monthly soil surface elevation change and determined its relationship to groundwater changes at a mangrove forest site along Shark River, Everglades National Park, Florida. We combined the use of an original design, surface elevation table with new rod-surface elevation tables to separately track changes in the mid zone (0–4 m), the shallow root zone (0–0.35 m), and the full sediment profile (0–6 m) in response to site hydrology (daily river stage and daily groundwater piezometric pressure). We calculated expansion and contraction for each of the four constituent soil zones (surface [accretion and erosion: above 0 m], shallow zone [0–0.35 m], middle zone [0.35–4 m], and bottom zone [4–6 m]) that comprise the entire soil column. Changes in groundwater pressure correlated strongly with changes in soil elevation for the entire profile (Adjusted $R^2 = 0.90$); this relationship was not proportional to the depth of the soil profile sampled. The change in thickness of the bottom soil zone accounted for the majority ($R^2 = 0.63$) of the entire soil profile expansion and contraction. The influence of hydrology on specific soil zones and absolute elevation change must be considered when evaluating the effect of disturbances, sea level rise, and water management decisions on coastal wetland systems.

Introduction

Soil surface elevation is an important response variable in wetland environments (Childers et al. 1993). Soil elevation affects hydroperiod, inundation frequency, and soil oxidation-reduction state. The hydrological conditions of a site are known to substantially affect soil processes including sedimentation, erosion, and the shrink and swell of soil materials. Soil elevation and surface flooding have been identified as important factors in wetland species colonization, recruitment, and survival (McMillan 1971; Rabinowitz 1978a,b; Ellison and Fransworth 1993; Cornu and Sadro 2002). Changes in soil surface elevation can be an important indicator of soil processes that are linked to hydrology, as well as those attributed to bioturbation (Ford and Grace 1998), decomposition (Cahoon et al. 2003), and subsidence (Cahoon et al. 1995). Soil surface elevation change is an integration of several processes occurring within the soil profile; yet most methods used to measure surface elevation changes do not distinguish among processes within the profile (Kaye and Barghoorn 1964; Childers et al. 1993; Cahoon et al. 1995). The elevation loss from subsidence and the elevation gain from accretion are incorporated into the absolute change in soil elevation. It is possible to partition the change in soil elevation into its component processes of surface accretion and subsurface expansion or compaction using the surface elevation table-marker horizon approach (Cahoon et al. 1995).

In a 3-yr study of a coastal mangrove forest along Shark River, Everglades National Park, Florida, soil surface elevation was found to vary linearly ($R^2 = 0.38$) with surface water stage 15–30 d prior to sampling (Smith and Cahoon 2003). The investigation was limited in that the benchmarks used to measure soil elevation extended just 4 m into the soil and stopped approximately 2 m above the limestone bedrock. Processes occurring below the 4-m deep benchmark were not included in the elevation readings. The influence of processes within the active root zone (e.g., root growth and

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*Corresponding author; current address: National Park Service, South Florida/Caribbean Inventory and Monitoring Network, 18001 Old Cutler Road Suite 419, Miami Florida 33157; tele: 305/252-0347; fax: 305/253-0463; e-mail: Kevin_R_Whelan@nps.gov decomposition or shrink and swell) on soil elevation could not be determined because the benchmarks integrated processes over the entire 4-m soil column. Because of these limitations we added sampling devices that allowed us to measure the shallow active root zone (0–0.35 m) and the deeper soil zone (4–6 m).

We present here a study of soil elevation dynamics in the lower Shark River drainage basin that includes the entire soil profile and distinguishes between three depths within the soil profile; 0–0.35, 0–4, and 0–6 m. Our main objective was to investigate the relationship among changes in soil surface elevation and changes in the hydrological parameters of river stage and groundwater piezometric head pressure at the site over the three depths. We wanted to determine the relative contribution to soil elevation by each of the four components of the soil profile: surface (i.e., accretion), shallow zone (active root zone, 0–0.35 m), middle zone (0.35–4 m), and bottom zone (4–6 m).

A comprehensive understanding of the influences of hydrology on the soil profile at this site is of considerable importance. The site is located in the Shark River estuary downstream of the Shark River Slough, receives freshwater inputs from the Greater Everglades drainage, and is under the influence of upstream water management practices of the Greater Everglades. The Everglades drainage is currently undergoing an ecosystem restoration concentrating on modifying water deliveries to mimic predrainage flows. In addition to the changing freshwater flows linked to restoration, this mangrove forest is affected by sea level rise. Determining how hydrology influences the specific soil zones and surface elevation will allow managers to make more informed decisions regarding these two opposing hydrological processes.

Materials and Methods

SET THEORY

The Surface Elevation Table (SET), based on the design of Boumans and Day (1993), allows for precise measurements of soil surface elevation (±1.4 mm total error; Cahoon et al. 2002a). The SET consists of a mechanical arm that is attached to a benchmark and leveled, establishing a fixed measuring point. Typically each SET has four fixed measurement locations (directions), where nine measuring pins are lowered to the soil surface to obtain a relative soil elevation. The elevation is the mean of 36 measuring pin readings per benchmark. SETs have been successfully used to monitor changes in elevation in a number of wetland environments (Cahoon et al. 1999). They have been used to monitor mangrove vertical accretion and subsidence (Cahoon and Lynch 1997) and to follow the response of soil elevation to season (Childers et al. 1993), water management (Boumans and Day 1994; Hensel et al. 1999), vertebrate herbivores (Ford and Grace 1998), and hurricane disturbance (Cahoon et al. 2003).

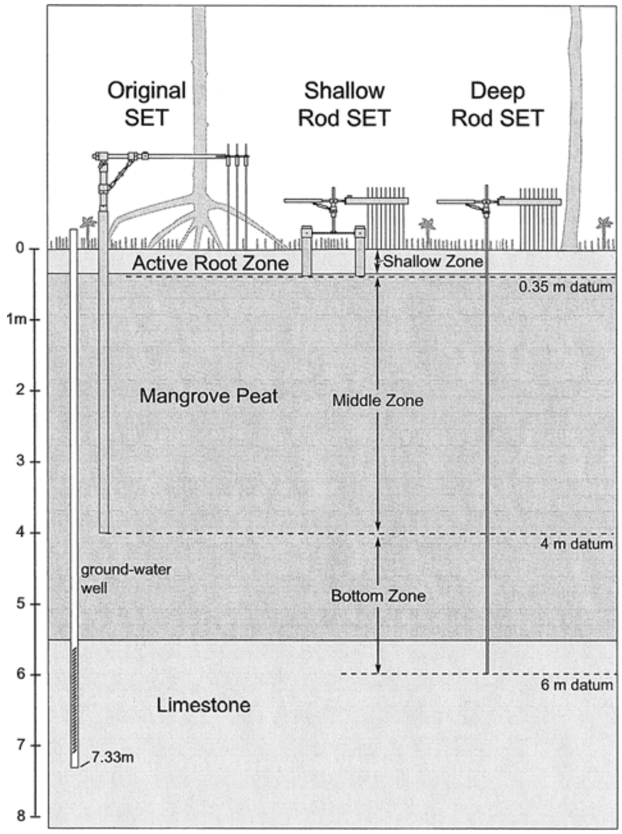

Fig. 1. Profile of the substrate showing the original-SET, deep-RSET, and shallow-RSET, groundwater well, and relative depth of each benchmark at Shark River mangrove site. (Adapted from Cahoon et al. 2002b). Drawing at 1:24 scale.

New SET designs have recently been described that measure the change in soil elevation of specific parts of the soil profile (e.g., root zone, below the root zone; Cahoon et al. 2002b). At the Shark River, the shallow-rod surface elevation table (shallow-RSET) benchmarks were installed to a depth that measures elevation change in the majority of the active root zone (top 0.35 m of the soil profile). The deep-rod surface elevation table (deep-RSET) benchmarks were driven into bedrock and measure the full soil profile. The original design SET (original-SET) benchmarks used by Smith and Cahoon (2003) were driven to approximately 4 m (Fig. 1). Further information on the design and accuracy of the original-SET and RSETs can be found in Cahoon et al. (2002a,b). By using a combination of SET designs at a single study site, it is possible to partition changes in soil elevation among specific parts of the soil profile, such as the shallow root zone and deeper soil zones (Fig. 1). By determining the absolute change for each depth zone we can calculate expansion and contraction for each zone (surface [accretion and erosion, above 0 cm], shallow [active root, 0–0.35 m], middle [0.35–4 m], and bottom [4–6 m]) of the profile.

Site Description

Vegetation

The study site, SH3 of Smith and Cahoon (2003), is located near the mouth of the Shark River (25°21′50.3″ N 81°4′42.2″W, 1984) in a mature mixed mangrove riverine forest comprised of *Rhizophora mangle* (L.) (red mangrove), *Laguncularia racemosa* (L.) Gaertn. (white mangrove), and *Avicennia germinans* (L.) Stearn (black mangrove). The site has a sparse understory. The canopy ranges in height from 13 to 17 m. The site has mixed tides. During the study period Shark River had a daily average conductivity of 40 mS cm^{-1} and varied between a low of 25 mS cm^{-1} and a high of 51 mS cm^{-1}. Shark River discharge was greatest at the end of the wet season, from September to November for 2002.

Soil Profile

The soil profile of this site was determined from the well drilling log (Anderson unpublished data; Fig. 1). The mangrove peat was 5.5 m in depth. The peat matrix lay directly on top of limestone, into which the well was drilled 1.8 m. The transition between the peat matrix and limestone was rapid. The limestone-peat interface was difficult to drill but had softer material below it. Otherwise, the entire peat layer was of similar constituency. No clay deposits were encountered during the drilling.

Cohen (1968) described the stratiography of the mangrove soil column at the mouth of Little Shark River, a location approximately 2.5 km away from SH3. He found that the mangrove peat was 3.81 m in depth and the total depth to bedrock at the site was 3.86 m. The peat types did not have recognizable petrographic constituents. All of the peat types were marine or brackish and dominated by *R. mangle*. There was a general increase of fine granular debris at the top and bottom of the profile. Fine granular debris comprised approximately 35% of the sample at the top and bottom of the core. At the top of the core it was suggested that an increase in fine-grained marine carbonates were responsible for this high number. The increase in fine granular debris at the bottom of the core may be due to greater amounts of degradation of the organic constituents of the peat. Pyrite content was relatively high (2–18%) throughout the core suggesting reducing conditions. Fusinite only occurred at the bottom of the core and comprised a small percentage of the constituents. There were no clays reported from this core.

TABLE 1. Depth of benchmark (m) for each SET and dates of establishment. Elevations for Group 3 SETs (mm) only with the first elevation on November 2, 2002, and second elevation on February 10, 2005 (NAVD 88 Geido 99).

Device establishment date	Group 1	Group 2	Group 3	First elevation	Second elevation
Shallow-RSET February 28, 2002	0.35	0.35	0.35	338	338
Original-SET July 16, 1998	4.04	4.09	4.32	405	405
Deep-RSET February 28, 2002	5.47	6.08	6.57	131	131

Preliminary sampling of the mangrove peat hydraulic conductivity (at a site 4 km away) yielded relatively low values (hydraulic conductivity field saturation method [Guelph permeameter] = k_{fs} = 1.87 m d^{-1}, see Hughes et al. 1998), which suggest slow water transmittance through the surface layer of the peat (Anderson et al. 2001).

SET Installation

We installed three groups of SETs within 18 m of each other and 45 m of Shark River. All groups were within 15 m of a U.S. Geological Survey (USGS) hydrological monitoring station (USGS station #252149081044301, described below). Each group included one shallow-RSET, one original-SET, and one deep-RSET along with four feldspar marker horizons (Cahoon and Turner 1989). The three original-SETs, used in the Smith and Cahoon study (2003), were installed on July 16, 1998. Three shallow-RSETs and three deep-RSETs were installed on February 28, 2002 (Table 1). On March 18, 2002, four separate layers of feldspar (0.5–3 mm deep) were laid as marker horizons with each group for a total of twelve new marker horizons. Shallow-RSET benchmarks were installed to a depth of 0.35 m. The original-SET benchmarks (76-mm [3″] diameter aluminum pipe, 1-mm thick wall) were driven approximately 4 m deep. The deep-RSET benchmarks (1.43-cm [9/16″] diameter stainless steel rods) were driven to approximately 6 m deep (Table 1). All SETs and feldspar markers were measured monthly from March 18, 2002, to March 21, 2003. Measurements were taken during low tide exposure on the same day. Two sampling events occurred with minimal water (a few puddles) present on the soil surface. On November 9, 2002, and February 10, 2005, a period of 2 yr and 4 mo, we surveyed the elevation of only the group number 3 shallow-RSET, original-SET, and deep-RSET with standard survey methods (±3 mm). There was no movement of the SET devices in relation to an established benchmark, suggesting that the assumption of a stable datum (Childers et al. 1993; Cahoon et al. 1995, 2002b; Cahoon and Lynch 1997) was valid during the study (Table 1).

Hydrological Data

The hydrological conditions investigated were daily rate of change in groundwater piezometric pressure and river stage. Groundwater head pressure was collected from a USGS station installed at the site in 1996 (Anderson and Smith 2005; Fig. 1). A piezometer recorded groundwater head pressure of the shallow coastal aquifer in a layer of limestone (hereafter referred to as groundwater). The 7.33-m piezometer consisted of threaded 7.62-cm diameter PVC pipe that was screened (0.20 slot PVC) from 5.7 to 7.2 m depth. The slotted part of the well was entirely within the limestone. The well was sealed with formation packer at 5.5 m depth, the interface of the limestone and the peat layer, to prevent vertical flow. Piezometric head pressure measurements were collected at hourly intervals. The pressure transducer was located at the depth of the well screen (for further details see Anderson and Smith 2005).

Shark River stage data were obtained from the Shark River hydrological monitoring station of Everglades National Park located 2.37 km downstream from SH3. This station records tidal influences as well as seasonal changes in river discharge for the area. Tidal flooding occurred at the site when the Shark River stage was above 0.07 m (Fig. 2). Shark River stage data were collected hourly. The groundwater piezometric head pressure and the Shark River stage were reported in North American Vertical Datum (NAVD) 88 datum (Geiod 99) (Fig. 2). Hourly Shark River stage and groundwater head pressure for the interval from December 13, 2002, to January 9, 2003, are included in Fig. 2. We used daily averages of the above parameters in order to remove the diurnal tidal signal. The daily averaged signal of these parameters shows the monthly lunar influences on the tide (Provost 1973), annual change in sea level (Provost 1973), and the seasonal changes in water level due to the regional wet season (Fig. 2). The hourly tidal signal was assumed to have minimal effect on our SET

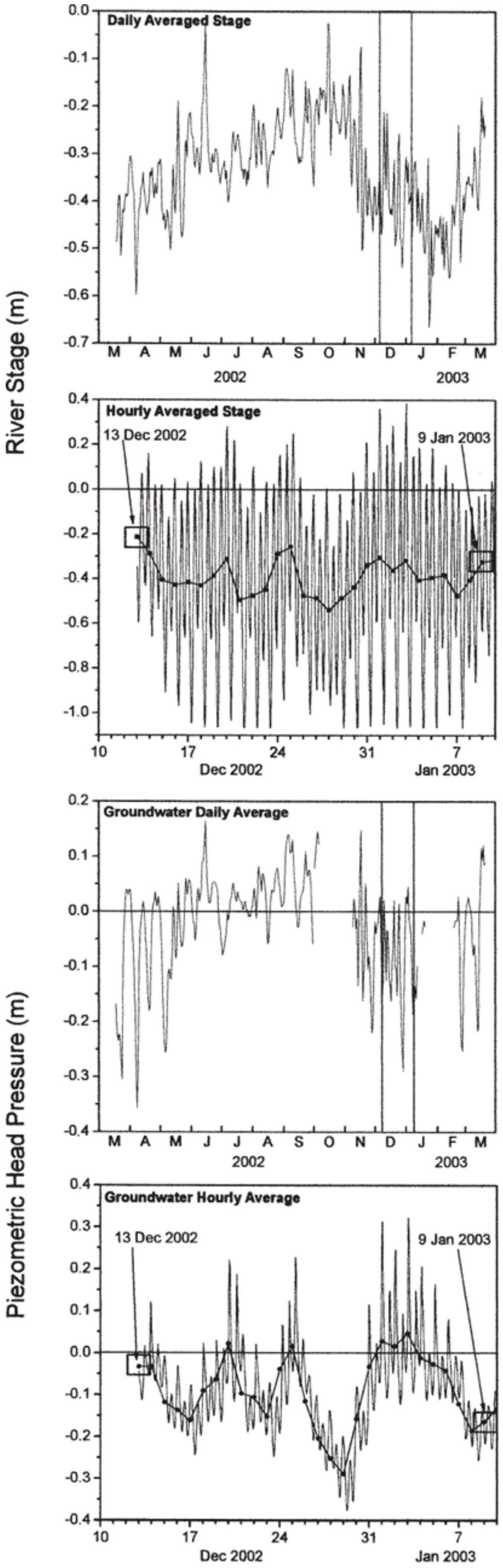

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Fig. 2. Hydrograph of daily averaged Shark River stage, hourly Shark River stage interval from December 13, 2002, to January 9, 2003, daily averaged groundwater piezometric head pressure, and hourly groundwater piezometric head pressure interval from December 13, 2002, to January 9, 2003 (m).

measurements because elevation data were always collected at low tide. Sensor malfunction resulted in the loss of daily groundwater piezometric head pressure data from October 7, 2002, to November 8, 2002, an interval that included the October 10 SET sample measurement.

DATA ANALYSIS

Soil elevation at each SET benchmark was averaged across all measuring pins in four directions ($n = 36$) for each sampling event. To determine the average daily rate of change (DRC) in the soil elevation between sampling events we used the following formula:

$$\mathrm{DRC} = \frac{\text{average soil elevation } (X_{t+1} - X_t)}{(\#\text{ days in interval})} \qquad (1)$$

Where X_t is average elevation at time t and X_{t+1} is the average elevation at time $t + 1$. The DRC for all hydrological metrics were determined in a similar fashion. River stage averaged for day X_{t+1} was subtracted from river stage averaged for day X_t and divided by the number of days in the interval. The daily average hydrological metrics were used in the analysis to remove hourly tidal effects (Fig. 2).

Within the three SET types, we used forward stepwise multiple regression to investigate the relationship between daily rate of change in soil elevation for each of the three benchmarks and the rates of change in the hydrological parameters and accretion. Stepwise multiple linear regression was used in order to discern the most important hydrologic variable associated with incremental elevation change. Stepwise regression not only allows for the identification of the most parsimonious model, but accounts for correlation among two or more variables (Zar 1999). All parameters included in the models were tested for collinearity and normality of the residuals (Quinn and Keough 2002). All models were analyzed using STATISTICA 5.0 (Statsoft Inc. 1996) and SPSS 11.0 (SPSS Inc. 2001). The final models included the two hydrological parameters: DRC in groundwater piezometric pressure and DRC in river stage. Within each SET type, we used a data set reduced from 36 data intervals (12 monthly intervals × 3 benchmarks) to 30 data intervals as a result of the hydrological data gap for groundwater piezometric pressure. Because there was only one well at the site, the hydrologic data was used three times, once for each SET type analysis. This may call into question the independence of the hydrology well data. We felt justified in presenting the hydrologic data with individual SET data to emphasis small scale spatial variation in soil surface elevation, and we had no reason to expect hydrological variation over this small distance mainly due to consistency in the soil matrix.

We felt that a regression using interval rate of change (as opposed to a regression of cumulative change) was justified because the focus of the study was to discover the relationship between elevation change and hydrologic variable from one sampling interval to the next. Interval data should reduce the influence of any serial correlation; due to the length of time between samples (monthly intervals), we felt that there was little influence of prior values on the relationships within a given interval. Regressions between the interval rate of change of soil elevation and the interval rate of change of hydrologic variables have been used previously (Childers et al. 1993).

By using the absolute change for each benchmark depth sampled by the three types of SET, we could calculate expansion and contraction for each component of the soil profile using the following formula:

$$\begin{aligned} &\text{Entire profile expansion and contraction} \\ &\quad = \text{Accretion} + (\text{shallow-RSET} - \text{Accretion}) \\ &\qquad + (\text{original-SET} - \text{shallow-RSET}) \\ &\qquad + (\text{deep-RSET} - \text{original-SET}) \end{aligned} \qquad (2)$$

Thickness of the entire soil profile is equal to the sum of surface accretion (above 0 m) and changes in thickness of the active root zone (0–0.35 cm), the middle zone (0.35–4 m), and the bottom zone (4–6 m).

Results

SITE HYDROLOGY

Both seasonal and monthly lunar influences were important for the hydrological conditions at the site (Fig. 2). The highest monthly mean stages at Shark River were in September and October (−0.23 and −0.19 m, respectively), typical for this drainage. The high river stage was a result of the maximum discharge of accumulated water from the wet season (June–September, Fig. 2). Groundwater piezometric head pressure was also high during September and October (0.06 and 0.12 m, respectively) due to hydrological recharge from the wet season. Daily river stage was a reflection of monthly lunar tidal flooding, wet season river discharge, and annual sea level variability (thermal expansion, Provost 1973).

There was moderate correlation between the two hydrological metrics used in the multiple regression with an $r = 0.72$ for Shark River stage to groundwater piezometric head pressure. Tolerance values were above 0.547 and variance inflation factors were less than 1.829, suggesting that despite some correlation between predictor variables, collinearity was not a serious issue for these data (Neter et al. 1996; Quinn and Keough 2002).

ACCRETION

The feldspar marker horizons did not become completely covered until 172 d after installation (September 10, 2002). The marker horizons were covered with mineral, organic, and root matter. The annual accretion rate was 6.64 ± 0.56 mm yr^{-1} (±1 SE). Sediment deposition values were intermittent in nature with high rates in October 2002 and March 2003 (Fig. 3). Slight erosion was evident during the November to December 2002 period (−1.8 mm) and the December 2002 to January 2003 (−0.8 mm) sampling.

SOIL ELEVATION

Changes in absolute soil surface elevation for both the deep-RSETs and original-SETs followed a similar pattern (Fig. 3). Both devices recorded the highest mean soil elevations at the end of the wet season (8.89 mm on October 10, 2002, for the original-SET and 15.14 mm on November 9, 2002, for the deep-RSET) and the lowest mean elevations during the dry season (January 9, 2003; −2.24 and −0.06 mm, respectively). The shallow-RSETs had a distinctly different pattern of soil surface elevation, with the highest elevation at the end of the wet season (6.83 mm on November 9, 2002) and the lowest early in the wet season (−0.66 mm on June 3, 2002, Fig. 3).

RELATIONSHIPS BETWEEN SOIL ELEVATION AND HYDROLOGY

The daily rate of soil elevation change of the shallow-RSET was partially explained (Adjusted $R^2 = 0.16$) by a negative relationship with the DRC of the river stage at the site (Table 2). That is, as river stage increased, the soil elevation that was influenced by the shallow soil zone decreased (Fig. 4). The rate of soil elevation change of the original-SET was positively related with the DRC of the groundwater head pressure (Adjusted $R^2 = 0.61$; Fig. 4, Table 2). This model was run with a reduced data set ($n = 28$) due to a one time sampling error of original-SET number 2. The DRC of soil elevation for the deep-RSET had a strong positive relationship to the DRC of the groundwater head pressure (Adjusted $R^2 = 0.90$; Fig. 4, Table 2). When groundwater head pressure increased the soil

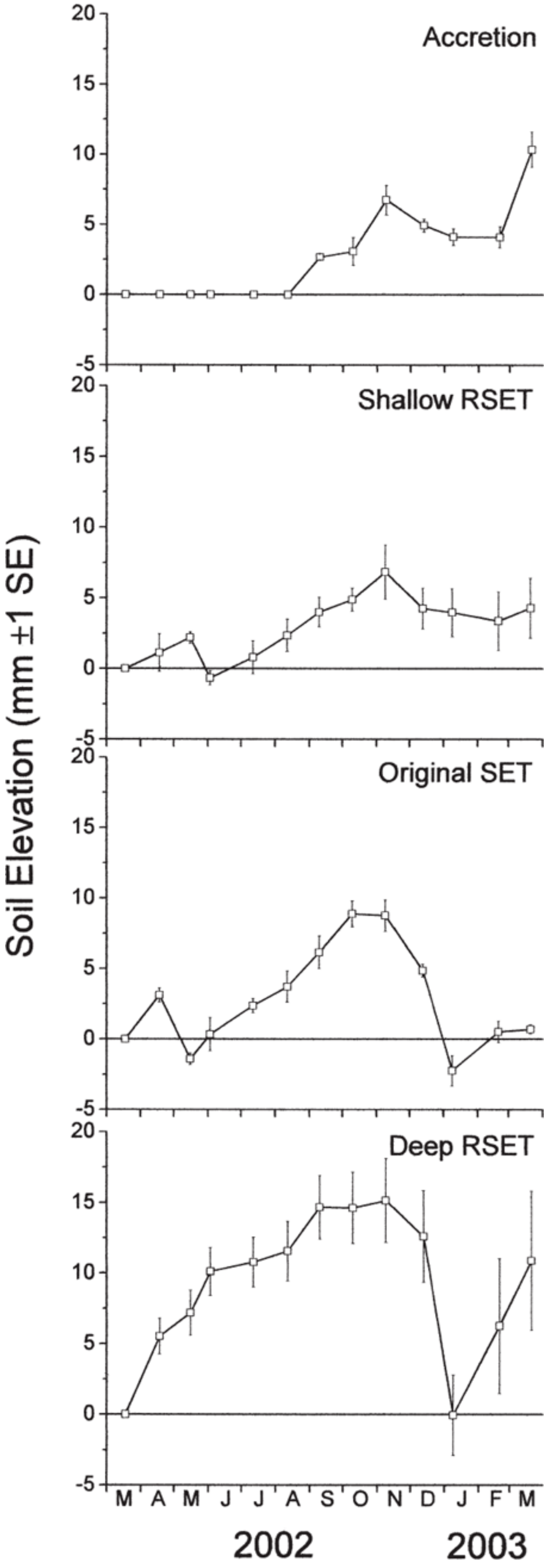

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Fig. 3. Mean absolute soil surface elevation (±1 SD) for accretion, shallow-RSET, original-SET, and deep-RSET.

TABLE 2. Regression equations and statistical results for daily rate of change (DRC) of surface elevation and DRC of best fit hydrological parameters for the three SET types used in this study.

Y (dependent variable)	m (slope)	X (independent variable)	b (intercept)	F	df	Adjusted R^2	n	p
DRC shallow-RSET	−0.012	DRC river stage	0.08	3.69	2,27	0.16	30	0.0383
DRC original-SET	0.040	DRC groundwater head pressure	−0.068	42.35	1,26	0.61	28	0.0001
DRC deep-RSET	0.074	DRC groundwater head pressure	−0.067	259.7	1,28	0.90	30	0.0001

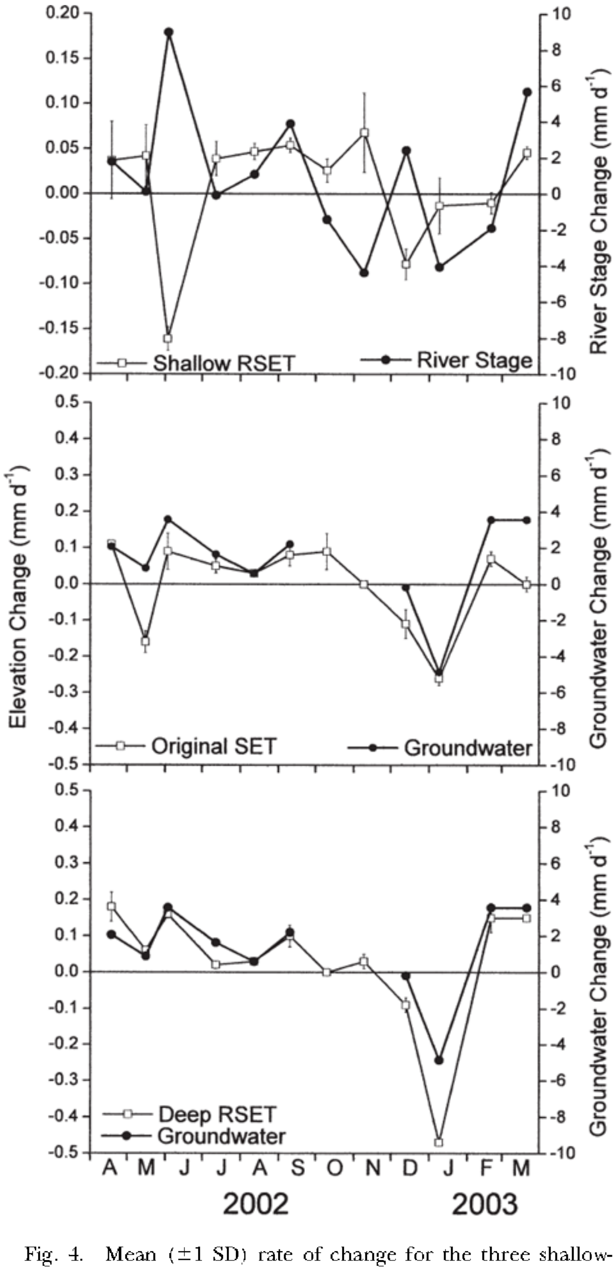


Fig. 4. Mean (±1 SD) rate of change for the three shallow-RSETs and the rate of change in river stage, three original-SETs and rate of change in groundwater piezometric head, and three deep-RSETs and rate of change in groundwater piezometric head.

elevation increased for both the original-SET and the deep-RSET.

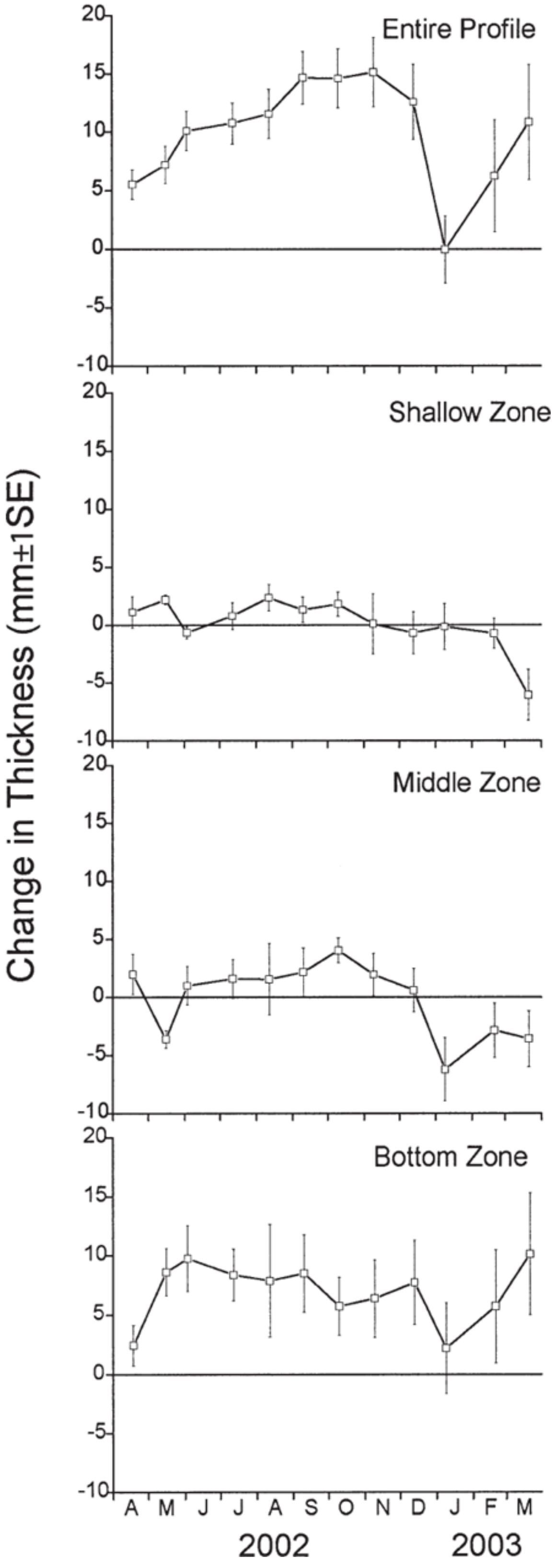
CONTRIBUTION OF EACH ZONE TO EXPANSION AND CONTRACTION OF THE ENTIRE PROFILE

We calculated the variation in thickness of each of the four constituent soil zones (Eq. 2) and the entire soil profile. We determined how much each of these soil zones contributed to absolute change of the entire profile by using a stepwise multiple regression model in which absolute change in the thickness of the entire profile was the dependent variable and the absolute changes in thickness for each soil zone were independent variables.

The contribution of each soil zone was not equivalent to the relative proportion of soil profile it comprised (Fig. 5). The bottom zone (4–6 m) accounted for 63% of the variation in the absolute change in thickness of the complete profile whereas the middle zone (0.35–4 m) accounted for only 22% (Fig. 5, Table 3). The bottom zone comprises only 31% of the entire profile whereas the middle zone comprises 63%. Accretion and the shallow zone were not significant contributors to the overall absolute change in thickness of the entire profile (Table 3).

Discussion

The soil surface elevation changed substantially during the year; the deep-RSETs recorded the greatest average elevation (15.14 mm) at the end of the wet season (November 9, 2002). The patterns of cumulative change in soil surface elevation were very similar for both the deep-RSET and original-SET, but the pattern of the shallow-RSET was distinctly different (Fig. 3). The overall annual accretion rate of 6.6 mm yr^{-1} was similar to the 4.4–7.8 mm yr^{-1} reported in another mangrove study in southwest Florida (Cahoon and Lynch 1997). The influence of accretion and erosion on the change in soil elevation was minimal over the duration of this study, as it was not a significant factor in any of the regression models. Elevation for all three SETs had changed substantially before accretion at the site was even measurable, indicating the importance of subsurface processes. In addition to accretion and soil swelling, shallow and deep subsidence have been reported to be significant



factors for the interpretation of soil elevation change (Cahoon et al. 1995). Here we were able to account for the opposing influences of subsidence and soil swelling by sampling the entire soil profile while including the processes of deposition and erosion in multiple regression models.

SUBSURFACE HYDROLOGICAL PROCESSES AND SOIL ELEVATION CHANGE

The entire mangrove peat-dominated soil profile was strongly influenced by groundwater. The rate of change in groundwater head pressure had a strong positive linear relationship to the rate of change in soil surface elevation for the deep-RSET (Adjusted $R^2 = 0.90$), suggesting that the entire soil profile is swelling in response to hydrological recharge. In this area, change in the daily groundwater piezometric pressure reflects freshwater recharging of the estuary and monthly tidal influences. Other mangrove SET researchers (Cahoon and Lynch 1997; Smith and Cahoon 2003) have reported seasonal response to soil elevation, but a direct relation to forcing by a hydrological parameter has not been previously shown. Because this particular peat has relatively low superficial hydrological conductivity and is typically continuously saturated, peat swelling may not be the only mechanism explaining this relationship. Nevertheless the tight coupling suggests this is the most likely mechanism driving changes in soil elevation.

Soil shrink and swell has been reported numerous times but almost exclusively in regards to soils with high clay compositions (Hillel 1971). As far as the authors are aware there are few reported shrink and swell observations in regards to wetland soils composed almost exclusively of peats driven by changes in groundwater head pressure. Those studies reported are confined to *Sphagnum* peatlands (Price and Schlotzhauer 1999) along with one reference to surface elevation changes in a salt marsh, but this was linked to semidiurnal surface tidal flooding (Nuttle et al. 1990). Our study indicates that changing groundwater head pressure was driving the monthly shrink and swell of the soil surface elevation in this peat matrix. Another study (Cahoon and Lynch 1997) suggested the importance of mangrove peat shrink and swell, in addition to growth, decomposition, and shallow subsidence as possible mechanisms for explaining annual elevation patterns. In our study, we were able to show that the peat matrix undergoes shrink

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Fig. 5. Mean (±1 SD) absolute change in thickness of the entire profile, shallow zone, middle zone, and bottom zone.

TABLE 3. Linear regression equations and statistical results for the absolute change in thickness of entire profile and the absolute change of each of the constituent components. Stepwise regression with $p < 0.01$ to enter and $p < 0.9$ to exit model. Overall model $R^2 = 0.85$. ns = not significant.

Y (dependent variable)	m (slope)	X (independent variable)	b (intercept)	t	p	Proportion of R^2	Proportion of soil profile
Change in thickness of entire profile	1.74			2.349	0.025		
		Middle zone	0.812	6.843	0.0001	0.22	0.63
		Bottom zone	1.197	13.340	0.0001	0.63	0.31
		Surface (accretion)			ns		<0.01
		Shallow zone			ns		0.06

and swell and that the majority of the expansion and contraction occurs in the bottom zone.

The Shallow Soil Zone

Soil elevation over the depth of the root zone had a moderate relationship with the DRC in Shark River daily stage (Adjusted $R^2 = 0.16$). The first five sampling events recorded no deposition since marker horizons were not completely covered; yet we recorded substantial change in surface elevation influenced by the shallow soil zone suggesting belowground influences. It should be noted that the marker horizons showed progression towards complete coverage by having less of the marker horizon visible each of the five successive sampling events. We were able to remove the influence of deposition and erosion by determining the relationship between thickness of the shallow zone (0–35 cm) and river stage. As daily rate of change for the river stage increased, the thickness of the shallow active root zone decreased ($R^2 = 0.24$, $F_{1,34} = 10.57$, $p < 0.004$). This analysis indicates that changing river stage has a stronger influence than previously noted for elevation change, but it is still only a moderate relationship. The lack of a strong hydrological link to the shallow soil profile is not wholly unexpected. Biological (root growth, crab burrow dynamics) processes rather than strictly hydrological influences dominate this shallow soil zone. Other possible explanations for the lack of a strong hydrological coupling are a shift in redox to more reducing conditions or a decline in root growth.

Erosion and deposition were not a great influence in explaining the change in surface elevation of the shallow-RSET over the short period of this study for the following reasons. The rate of deposition and erosion were not a significant parameter in the shallow-RSET model. The first five sampling events indicated substantial change in surface elevation influenced by the shallow soil zone when no deposition and erosion were measured. The model was rerun for only those periods with marker horizons measurements and no difference was found in the final model.

Cumulative Proportion of Profile Sampled and the Role of the Bottom Zone

The response of the soil elevation change does not appear to be directly proportional to the depth of the soil profile encompassed by the SET device. The original-SET (0–4 m) followed the groundwater influence ($R^2 = 0.61$), but not as strongly as the deep-RSET (0–6 m; $R^2 = 0.90$). Compared to the deep-RSET, the original-SET encompassed 2 m less of the soil profile, which reduced the coupling between change in soil elevation and change in groundwater piezometric pressure (slope of the regression equation $\beta_1 = 0.040$ for the original-SET versus $\beta_1 = 0.074$ for the deep-RSET, Table 2).

We used the proportion of the soil profile sampled by the original-SET as compared to the deep-RSET to predict the average elevation of the original-SET based on the corresponding deep-RSET readings. Original-SET number one benchmark depth was 4.04 m and the deep-RSET number one benchmark depth was 5.47 m, resulting in a proportion of the entire soil profile sampled by original-SET number one of 0.74 (i.e., 4.04/5.47 m). If the relationship was linear with proportion of soil profile sampled then the actual values should fall near the calculated values along the one to one line (Fig. 6). The values predicted for original-SET based on this ratio were higher than the actual elevation values recorded (Fig. 6), suggesting that the deepest 2 m of peat not encompassed by the original-SET have a disproportionately larger influence on the absolute soil elevation.

To further corroborate the importance of the influence of the bottom zone on overall soil profile expansion and contraction, we determined the percent of variation explained by each component zone to overall soil column expansion and contraction. We determined that the largest constituent zones, the middle and bottom zones, drive the expansion and contraction of the entire profile. These two parts account for 94.2% of the soil profile and explain 85% of the variance in overall soil profile expansion and contraction. The bottom

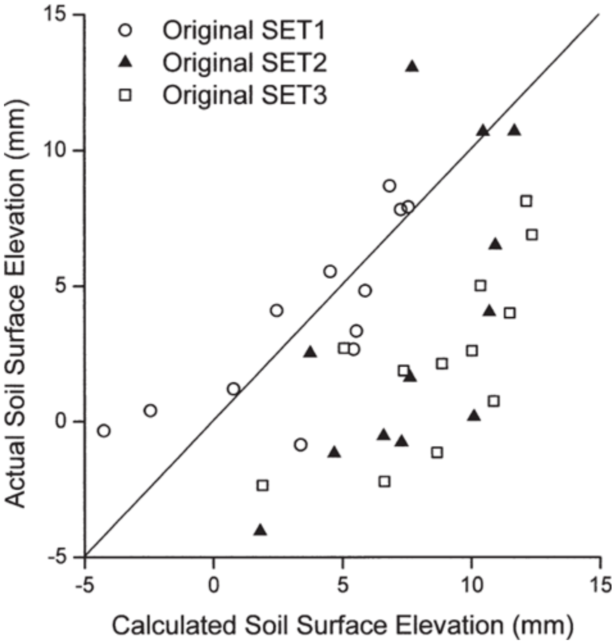

Fig. 6. Actual soil surface elevation of the original-SET (mm) versus calculated soil surface elevation (mm) (proportion of the deep-RSET). Dark solid line represents 1:1 ratio. n = 36.

zone accounted for 63% of the variation in the absolute change in thickness but comprised only 31% of the profile. The middle zone accounted for only 22% of the variation but comprised 63% of the profile (Fig. 5, Table 3). These data suggest that the bottom zone has a greater influence on overall change in soil surface elevation than would be expected based on its relative proportion and that in this zone changing groundwater pressure would be the most influential.

Our results indicate that increases in groundwater flow should have a direct positive effect on absolute soil surface elevation for the entire soil profile by expanding the bottom soil zone. Since expansion and contraction affects the water storage potential of the peat matrix it is an important consideration for studies of water balance and nutrient fluxes (Nuttle et al. 1990). The current hydrological restoration of the Everglades and increases in sea level will directly affect this mangrove forest. Any modification to freshwater flows via the Everglades Restoration will affect the elevation of the mangrove forest by expansion and shrinkage. In order to determine how other processes (bioturbation, organic production, decomposition, disturbance, and subsidence) will affect long-term change in soil surface elevation, researchers must account for this shrink and swell signal and remove it from the analysis. The influence of these hydrological processes must be taken into account in the context of monitoring the effects of hydrological restoration or sea level rise. Understanding the factors influencing the change in soil elevation as it relates to different parts of the soil profile will be critical when trying to predict long-term mangrove sustainability in an increasing sea level environment.

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