Global Change and Marsh Elevation Dynamics: Experimenting Where Land Meets Sea and Biology Meets Geology

J. Adam Langley, Marc V. Sigrist, James Duls, Donald R. Cahoon, James C. Lynch, and J. Patrick Megonigal

ABSTRACT. Coastal marshes must accumulate soil to keep up with rising sea levels. It is unknown how the response of these ecosystems to global change will influence their ability to continue to keep up with sea-level rise. Here, we describe an in situ experimental chamber approach for manipulating key environmental variables, such as atmospheric CO_2 and soil N availability, in a brackish marsh. We outfitted each chamber with surface elevation tables (SETs) to closely monitor soil elevation change, a sensitive indicator of marsh vulnerability to sea-level rise. Further, the design facilitates measurements of ecosystem exchange of CO_2, plant productivity, porewater chemistry, and other environmental parameters.

INTRODUCTION

Projecting the impacts of climate change, eutrophication, and other perturbations on ecosystems requires experimental manipulations. Large experimental facilities have been built and operated in all types of ecosystems over the past decades to provide such data. There are at least six characteristics that complicate experimental manipulations in tidal wetlands. First, such ecosystems can be quickly and irreversibly damaged by heavy foot traffic, so boardwalks must be built to minimize long-term impacts on vegetation and soils. Second, because many wetlands have deep, low-density, peaty soils, the permanent infrastructure, such as boardwalks and chambers, must be well anchored for stability. Third, tidal wetlands are often inundated by tides and can be under more than a meter of water during storm surges, which dictates that all buoyant equipment must be soundly fixed in place. All electrical service and sensitive equipment must be positioned high and be easy to remove during extreme flooding events. Further, emergency shutoff systems must be in place to cut off the electrical supply and gas exchange equipment during flood events. Fourth, the water that floods brackish marshes is saline and corrodes most metals. Fifth, the lack of shade means that UV-sensitive materials will degrade. Care must be taken to select UV-resistant materials, and even those must be monitored and frequently replaced. Sixth, high-latitude marshes may experience cold winters. Ice formation can severely damage even rigid and well-anchored infrastructure. Here we

J. Adam Langley, Marc V. Sigrist, James Duls, and J. Patrick Megonigal, Smithsonian Environmental Research Center, 647 Contees Wharf Road, Edgewater, Maryland 21037, USA. Donald R. Cahoon and James C. Lynch, U.S. Geological Survey, Patuxent Wildlife Research Center, 10300 Baltimore Avenue, BARC-East Bldg. 308, Beltsville, Maryland 20705, USA. Corresponding author: J. A. Langley (langleya@si.edu). *Manuscript received 13 May 2008; accepted 20 April 2009.*

describe a global change experiment in a brackish marsh that was designed to overcome these substantial technical challenges.

SITE DESCRIPTION

This study took place at Kirkpatrick Marsh, which is located on the Rhode River, a subestuary of Chesapeake Bay at the Smithsonian Environmental Research Center in Edgewater, Maryland. The site is dominated by the C_3 sedge, *Schoenoplectus americanus* (formerly *Scirpus olneyi*), and less so by two C_4 grasses, *Spartina patens* and *Distichlis spicata*. The soils at this site are organic (80% organic matter) to a depth of approximately 5 m. Mean tidal range is 30 cm. The high marsh zone is 40–60 cm above mean low water level and is inundated by 2% of high tides. Salinity averages 10 parts per thousand (ppt) and ranges from 4 to 15 ppt seasonally. Average daily low air temperature is −4°C in January, and the average daily high is 31°C in July.

To examine the interactive effects of elevated CO_2 and nitrogen addition, we identified 20 plots of similar plant composition in summer 2005. Each plot consisted of one octagon (2 m across) that would be enclosed in an experimental chamber to allow for atmosphere manipulation and an adjacent rectangular portion (2 × 1 m) that served as a reference plot to account for spatial variation and to gauge potential chamber effects.

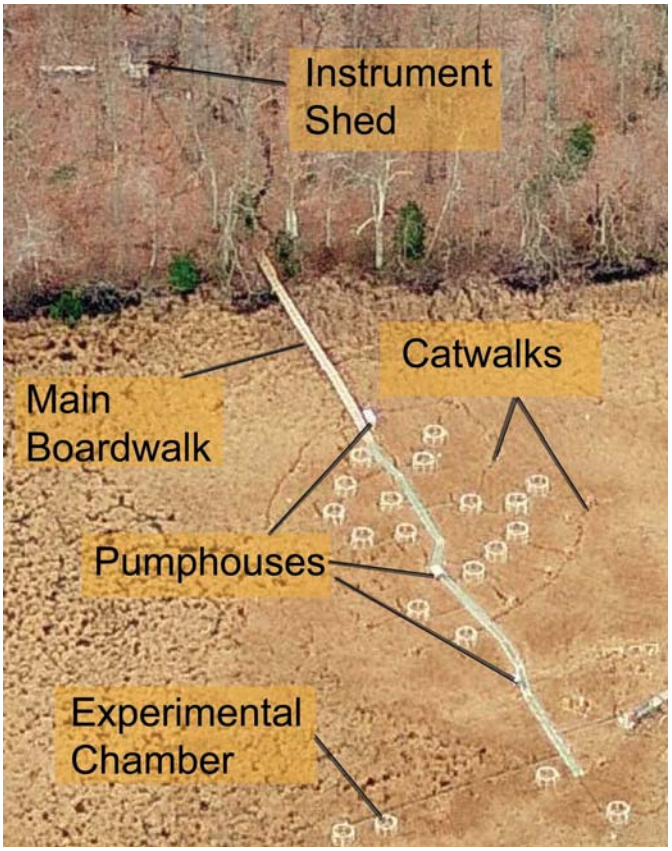

FIGURE 1. An overhead image of the entire CO_2 site. The main boardwalk connects to 20 experimental plots by smaller catwalks, the paths of which are visible. Gas samples are pumped via the pump houses to the analytical shed on the bank.

CONSTRUCTION

Walkways and Equipment Housing

A main boardwalk and a series of thinner, lighter "catwalks" were built to access each plot without continually walking on the marsh (Figure 1; see also Figures 4, 5). The main boardwalk, built perpendicular to shore, roughly bisected the experimental plots. Most of the horizontal surfaces of the boardwalks were fiberglass grating (50% open), which allowed light to penetrate through the boardwalks, sustaining plant life and providing excellent traction. The supports for the main boardwalk were built of 10 × 10 cm posts sunk 2 m into the ground. The catwalks departed from the main boardwalk, forming a perimeter around each experimental chamber (Figure 2). These catwalks were less than 30 cm above the ground to avoid shading the plots. They were built of fiberglass grating (30 cm wide planks) laid flat on supports built of 2.5 cm polyvinyl chloride (PVC) that were anchored more than 1 m into the marsh using segments of 2.5 cm PVC pipe. After all walks were in place, the marsh surface was rarely stepped upon directly.

Three small pump houses, which housed air sample pumps and remote datalogging equipment, were built alongside the main boardwalk. An analytical shed was constructed on the bank 5 m above sea level to house sensitive analytical equipment.

Open-Top Chambers

The chamber design followed that of a previous open-top chamber study in the same marsh (Drake et al., 1989), but with several major innovations to enhance durability and plot accessibility (Figures 2–5). In 2006, the chambers consisted of four major components: base, manifold, chamber skeleton, and chamber panels. The octagonal shape of the chamber was a compromise between two design goals. It approximated a cylinder, which was ideal

for uniform air mixing inside the chamber and minimizing dead spots. The flat surface of each side allowed us to enclose the chamber with eight flat panels that can be removed easily for access to the inside of the chamber.

The base of the chamber was an aluminum octagon (0.5 cm thick, with an L-shaped cross section) implanted 10 cm into the marsh surface. In the portion of the base that was implanted into the soil, 2 cm holes were cut to allow root growth to further stabilize the base. A hollow octagonal manifold (cross section, 30 cm high × 6.35 cm wide) was attached to the base to distribute inflowing air equally around the chamber (see Figure 2). Manifolds were built from welded aluminum (grade 6061-T5) covered with transparent acrylic panels that allowed light transmittance.

Mounted to the top of the manifold was the "skeleton," consisting of eight vertical legs supporting an octagonal ring oriented horizontally at the top. The skeleton was built from 2.5 cm diameter PVC pipe. The only custom pieces in the skeleton were three-way fittings on the octagonal ring that join two PVC pipes in the ring with one leg. The joint was made by tapping female thread into the side of a 45° elbow. The legs of the skeleton sat in welded supports on the top of the manifold.

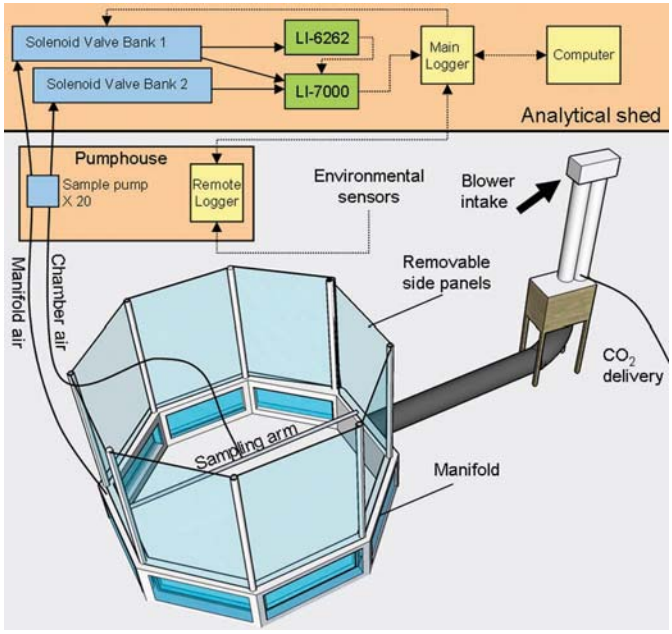

FIGURE 2. Schematic of an experimental chamber and gas sampling system. The ambient CO_2 chambers are the same except there is no CO_2 delivered into the blower stream. Solid (black) arrows represent air flow; dotted arrows (appearing light gray) represent information flow.

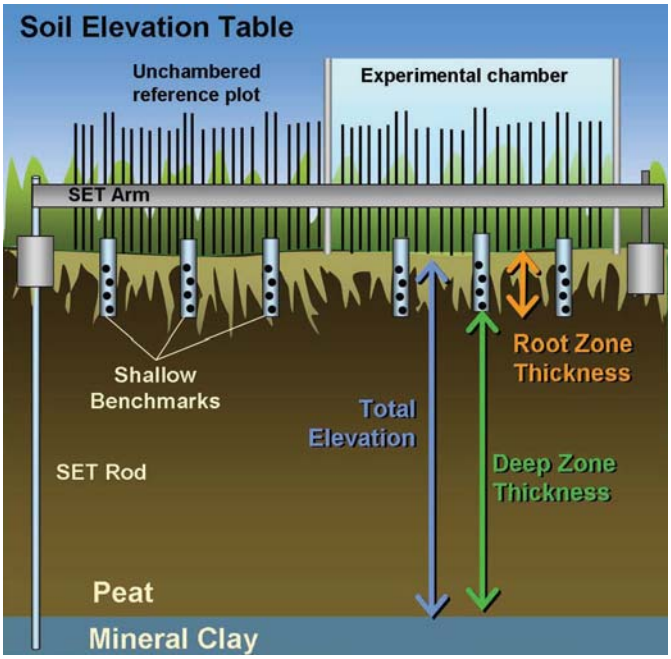

FIGURE 3. Schematic of the surface elevation table (SET) design. The SET arm is periodically connected to the SET rod benchmark, which has been anchored into the mineral clay underlying the peat profile. Pins are placed through holes in the SET arm to the soil surface to measure changes in elevation occurring over the entire profile. Any change in elevation of the shallow benchmarks must occur as a result of processes occurring beneath the root zone. Root zone changes are calculated by subtracting deep zone elevation change from total elevation change.

Removable rectangular panels were made from aluminum (grade 6063-T52), covered with infrared (IR)-transparent film (Aclar 22A, Honeywell) that was taped on using transparent UV-resistant tape (3M, 851). The film does not absorb IR radiation as do other films and therefore heat is not allowed to accumulate. The panels were attached to the PVC frame with custom-fitted PVC snaps so that any of the eight panels could be removed to access any portion of the plot. Further, panels were removed in the winter to prevent damage while CO_2 fumigation was terminated.

Finally, after the 2006 growing season, to conserve CO_2 and achieve a more stable CO_2 concentration by reducing wind incursions, an octagonal frustum, or wind foil, was added to the chamber design (see Figure 5). The frustum was constructed of 1.9 cm PVC, angled inward at 45°, and covered with the same film to reduce wind incursions. The final dimensions of the chamber were 1.5 m in height, 2 m in diameter, and with 1 m sides; the volume is 6.5 m^3.

FIGURE 4. Photograph of SET measurements being made in summer 2006. Each pin is gently lowered to the soil surface, while applying minimal pressure so that the pin does not depress the soil surface. (Photograph by M. V. Sigrist.)

To move ambient air through the open-top chamber, a blower (Dayton, 5C095) was mounted on a stand 1.5 m above the marsh surface to avoid high tides. The blowers were placed at least 6 m away from each chamber and oriented to avoid shading the study area (see Figures 1, 2, 4). PVC chimneys (two 15 cm pipes per blower) were affixed vertically to the top of the blower intake so that the blowers would take in air from 4 m above the ground that was not influenced by biological activity on the ground and thus had relatively stable [CO_2]. The chimneys were capped to prevent rainwater from entering the blower. A 20 cm diameter duct fed air from the blower to the chamber manifold. Two hundred fifty-two 1 cm diameter holes (the same total area as the intact pipes) were drilled on the inside of the manifold, so that air would flow in the chambers equally from each side of the octagon. The blowers forced 12.5 m^3 per minute through the chambers, resulting in an approximate chamber air turnover rate of 2 min^{-1}.

Surface Elevation Tables

To take repeatable measurements of soil elevation, each plot was outfitted with a rod surface elevation table (SET; see Figures 3, 4) (Cahoon et al., 2002) modified to accommodate plot dimensions. Outside each experimental chamber, a posthole was dug roughly 15 cm in diameter and 20 cm deep. A 30 cm long PVC pipe (15 cm diameter) was placed vertically into the hole. In the center of the PVC pipe, a series of attachable stainless steel rods was driven with an electric hammer through the entire profile of organic matter (4–5 m depth) and anchored to the point of refusal (6–7 m) into the subsurface mineral clay underlying the marsh. Concrete was poured into the PVC pipe to secure the top of the SET rod.

To isolate the influence of root zone processes on elevation, we implanted "shallow benchmarks" to a depth of 30 cm. The vertical movement of these benchmarks results from processes that occur below the top 30 cm of soil. The benchmarks were made of aluminum pipe (5 cm diameter by 40 cm long). Several 1 cm diameter holes were drilled into the sides of the lower 10 cm of the pipe to allow roots to grow through and anchor the benchmarks in place. Six benchmarks were implanted to a depth of 30 cm under the path of the SET arm in each chamber, three inside the chamber and three outside. After

FIGURE 5. Photograph showing a chamber with a frustum that was added to all chambers before the 2007 growing season. The tubing leading to one set of porewater wells, the gas sampling tube, and the catwalk is also visible. (Photograph courtesy J. A. Langley.)

placement, solid caps were placed on the top of each pipe. All these perturbations, as well as boardwalks to service each plot, were completed in the summer of 2005, at least 9 months before the beginning of the experiment.

At intervals ranging from 1 to 3 months, the modified horizontal aluminum SET arm (4 m long compared to less than 0.5 m long for the original rod SET design) was attached to the top of the SET rod benchmark, leveled precisely, and affixed to an aluminum post at the other end. The arm provided a horizontal reference of known elevation across the soil surface; changes in the distance from this reference surface to the soil surface were a sensitive measure of changes in soil elevation. Fiberglass pins (3 mm in diameter), all exactly 91.0 cm in length, were placed through precision-drilled holes in the SET arm at 1 cm increments. Approximately 40 individual measurements were made in each chamber and 40 in each adjacent, unchambered reference plot. Each pin was carefully lowered to the soil surface and gently placed so that no litter or live plant obstructed the pin. The height from the SET arm to the top of each pin was measured to the nearest millimeter (mm), providing a measurement of total elevation. Changes in absolute soil elevation were partitioned into either the root zone (top 30 cm of soil) or the deep zone (below 30 cm). To measure elevation changes occurring in the deep zone, we lowered 2 to 4 pins to the surface of each of the six shallow benchmarks (three inside and three outside each chamber) and measured in the same manner. We calculated the change in elevation resulting from processes occurring in the root zone, ΔE_R, from the two measured variables following the equation $\Delta E_R = \Delta E_T - \Delta E_D$, where ΔE_T represented the change in total elevation and ΔE_D represented elevation change attributable to change in thickness of the deep zone. Surface accretion was also measured using feldspar marker horizons in each plot (Cahoon et al., 1995). To eliminate compaction during coring, the deposition rate was estimated by taking cryocores (Cahoon et al., 1996) and measuring the amount of soil deposited on top of the marker horizon.

Total soil elevation was strongly related to innate spatial and temporal variability of deep zone dynamics. Specifically, changes in the thickness of the deep zone followed mean monthly sea level through time, and distance from the bank predicted the amplitude of that oscillation. To isolate treatment effects on various soil elevation parameters, we accounted for variation by referencing SET measurements in experimental chambers to those in the adjacent, unchambered reference plots, so that relativized ΔE = experimental plot ΔE − reference plot ΔE, where E = the elevation parameter of interest. We used a repeated-measures multivariate analysis of variance (MANOVA) to test for changes in elevation through time; we used *t* tests to liberally detect chamber effects on elevation parameters at individual dates and a two-way analysis of variance (ANOVA) to test for treatment differences in surface accretion.

TREATMENT APPLICATION

CO_2 Delivery and Sampling System

Carbon dioxide was delivered to each of the 10 elevated CO_2 chambers at a rate of approximately 6 L min^{-1} to achieve a target concentration of 720 ppm, which is nearly double the current ambient concentration of 380 ppm. Each CO_2 delivery line was controlled with metered valves and fed into the intake chimney on the blower for each respective elevated chamber. Adding the CO_2 upstream of the blower ensured sufficient mixing before air entered the chamber through the manifold.

Two sample lines continuously pumped air from each of 20 chambers to instruments located in a nearby shed: one line sampled manifold air and the other sampled the chamber atmosphere. To achieve a representative sample of the chamber atmosphere, air was sampled with a 2 m long pipe oriented horizontally across each chamber. The pipe was 1.3 cm diameter PVC with caps on both ends and a series of 2 mm diameter holes at geometrically increasing intervals away from the center of the pipe. The geometry allowed air drawn from the center of the pipe to be a composite sample representing each point on a transect through the chamber equally. The sampling pipe was positioned horizontally and adjusted to roughly half the green canopy height to best represent the air that photosynthetic tissue experienced.

Air was pulled under negative pressure from each chamber a short distance to a Teflon-coated double diaphragm pump (Thomas Industries, 2107-CA14-TFE), from which it was pushed under positive pressure to the analytical shed (see Figure 1). To avoid drawing water into the pumps, they were plugged into normally closed float switches (Dayton 3BY75) that cut the power supply when the water level approached the height of the gas sampling lines. Each of the 40 lines entered a bank of solenoid valves (model 3V1, Sizto Tech Corporation), then flowed into a common line, one for manifold lines and one for chamber lines. The two solenoid valves controlling each chamber opened simultaneously, one with manifold air and the other with chamber air; the other solenoid valves remained closed so that the contents of only one chamber at a time passed through the common lines to the gas

analyzers. Each chamber was sampled for 2 min to allow ample time for air in the common portion of the system to be flushed out before measurements were logged, which meant that each chamber was sampled at least once every 40 min.

One infrared gas analyzer (IRGA) measured the difference between a chamber's manifold air (i.e., incoming air) and a dry, zero-CO_2 reference gas. A second IRGA measured the difference between manifold air and chamber air. This configuration maximized our ability to precisely measure absolute CO_2 concentration and to accurately measure the CO_2 concentration difference between two locations. A LI-6262 (Licor, Lincoln, NE) had dry, zero-CO_2 air cycling through the reference cell and the manifold air passing through the sample cell. A Li-7000 (Licor) had the manifold air passing through the reference cell and chamber air passing through the sample cell. Cell A of the LI-7000 was referenced to an analog signal from the LI-6262 as the absolute concentration of CO_2 and H_2O in the manifold air.

We monitored the manifold line to determine how much CO_2 was being delivered to each manifold. The chamber air sampling line allowed us to monitor the actual chamber atmosphere and to fine tune the CO_2 delivery rate to achieve our target concentration in the chamber atmosphere, accounting for photosynthetic drawdown and wind incursions.

Nitrogen Fertilization

A total of 25 g N $year^{-1}$ was applied to each high-N plot. Ammonium chloride was dissolved in 5 L brackish water from the nearby Rhode River, the subestuary adjacent to the site. At five dates (approximately monthly, avoiding high tides) throughout the growing season we used backpack sprayers to deliver the fertilizer (equivalent to 5 g N) solution to 10 plots. Then, the fertilizer solution was rinsed from standing vegetation with another 5 L unamended river water applied with backpack sprayers. Each fertilization treatment simulated 5 g N m^{-2} in the equivalent of 0.5 cm river water. The 10 unfertilized chambers received 10 L unamended river water applied in the same manner. The river water was taken from the tidal fetch area adjacent to the marsh. Mean annual [NH_4^+] in that water ranges from 32 to 82 μg L^{-1}, with a mean of 52, and salinity has ranged from 4.0 to 10.6 ppt, with a mean of 6.7, over the past 20 years (growing season means from biweekly sampling; Thomas Jordan, unpublished data). Assuming the added NH_4Cl integrated into the top 40 cm of porewater (as our sampling indicates), and excluding losses from the ecosystem or plant uptake, we estimated that this fertilization would have increased porewater salinity by a maximum of 0.05 ppt, less than 1% of normal salinity.

MEASUREMENTS

The chambered experimental plots consisted of two halves, one-half geological and one-half biogeochemical. All sampling that involved disturbance of soil was performed on the biogeochemical half. All elevation measurements, which were considered to be more sensitive to soil disturbance, were performed on the geological half.

Aboveground Biomass

We estimated peak aboveground biomass with a combination of allometry and harvested subplots (Erickson et al., 2007). At the end of July of each year, eight 30 × 30 cm quadrats were placed in prescribed locations in each plot, six inside the chamber and two in an adjacent unchambered control plot. In the quadrats, each *Schoenoplectus americanus* stem was counted and nondestructively measured for total height, green height, and width at half-height. In the corner of each quadrat, we clipped and removed all vegetation and litter in a 5 × 5 cm area. Vegetation was sorted according to species. We measured the clipped *S. americanus* stems for total height and width. Clippings were dried for 72 h at 60°C and weighed. We measured length and width on a subset of freshly clipped stems. We used the calculated relationship between linear dimensions and dry mass ($r^2 > 0.9$) to estimate the mass of each live *S. americanus* stem. To estimate *Spartina patens* and *Distichlis spicata* mass, we scaled up from mass in the clipped areas to total chamber area.

Root Productivity

Three soil cores (30 cm depth × 5 cm diameter) were taken from each plot and replaced with cylindrical ingrowth bags (30 cm height × 5 cm diameter). The bags were constructed from 1 cm mesh and filled with milled, moistened peat so as to achieve the bulk density of in situ peat, 0.12 g cm^{-3}. Bags were implanted in winter and removed in November the following year. Contents were washed over a 1 mm sieve. Large organic fragments were picked out by hand. Root mass was separated into fine (<2 mm diameter) and coarse (>2 mm) categories, dried for 72 h at 60°C, and weighed.

Porewater Wells

We implanted nine porewater wells (three replicates at each of three depths: 20, 40 and 80 cm) in each experimental plot. We built wells from 0.6 cm internal diameter rigid Teflon tubing (GE Polymershapes) plugged at the bottom with silicon caulk and open at the top, which extended 10 cm above ground. Sixteen holes (1 mm diameter) were drilled into the bottom 10 cm of the Teflon tube to allow ample conductance of porewater into the well. A vinyl hose (6 mm [OD], 3 mm inner diameter [ID]) was fastened to the top of each well and draped over the chamber for easy access from outside the chamber. Wells were flushed with 60 mL, equivalent to more than total well volume, and sampled monthly for a suite of chemical parameters using syringes.

Net Ecosystem Exchange (NEE)

The chambers were also designed to allow for measurement of net ecosystem exchange (NEE) of CO_2 between the atmosphere and the enclosed ecosystem (Figure 6). Periodically throughout the growing season, octagonal caps were placed on a subset of chambers. The purpose of the caps was not to render the chamber airtight, but to eliminate wind incursions and generate a consistent, predictable pattern of air flow through the chambers. The caps were octagons with a crossbeam built from 1.9 cm PVC pipe covered with the same IR-transparent film for the chamber panels. The film was perforated with 2 cm diameter holes. The gas sampling pipe, described above, was raised to a height roughly 30 cm below the cap and aligned with the cap perforations. This arrangement allowed us to measure the [CO_2] of air exiting each chamber after it had been influenced by soil and vegetation.

To estimate flow rate of air through the chamber, we cut a slit in the air delivery ducts from each blower and measured air velocity using a handheld anemometer (AM 4822, Mastech; www.p-mastech.com). We initially measured the velocity at a range of distances from the duct wall and determined that the mean of two measurements (centered at 4 cm and 9 cm from the duct wall) adequately estimated the average velocity for the entire cross section. Multiplying velocity (cm s^{-1}) and cross-sectional area (cm^2)

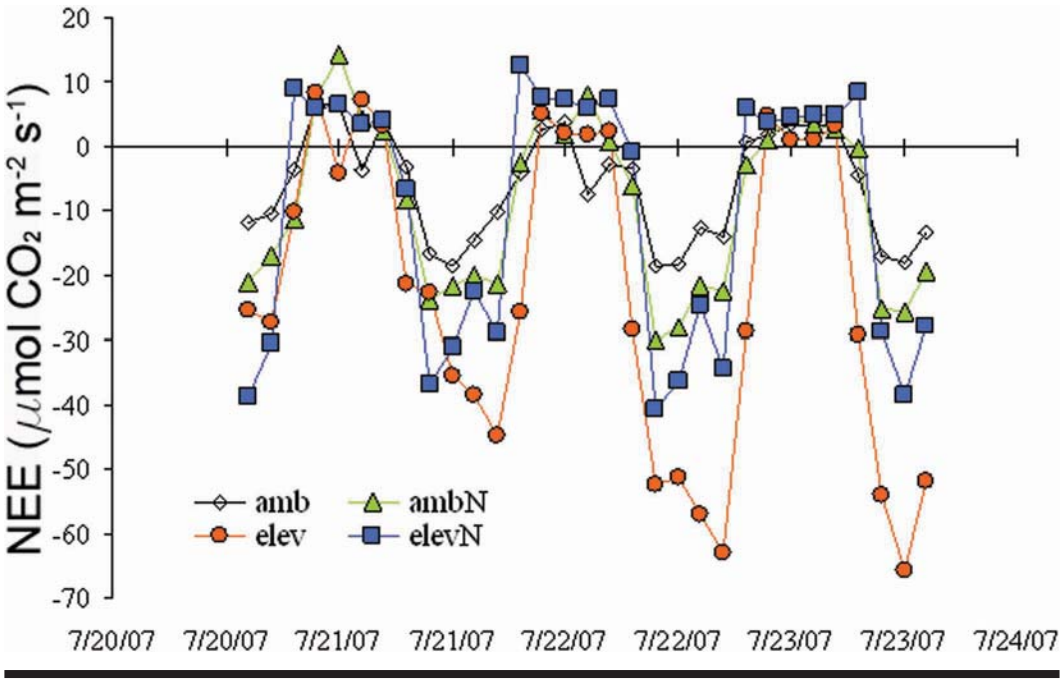

FIGURE 6. Net ecosystem exchange (NEE) of CO_2 over three days in July 2007. Negative values represent net uptake by the ecosystem. Generally, values are negative in summer daytimes when photosynthetic rate surpasses respiration rate. Each point represents the means of approximately 12 individual measurements from each of two replicate chambers binned into 2.4-h intervals. amb = ambient; elev = elevated; ambN = ambient N; elevN = elevated N.

yielded volumetric flow rate ($cm^3\ s^{-1}$). The volumetric flow rate was converted to mass flow using air temperatures from the site. We calculated NEE as $([CO_2]_{in} - [CO_2]_{out}) \times$ flow rate.

Because we did not want to incur chamber effects such as warming or rain exclusion, we measured NEE on a rotating subset of chambers balanced by treatment, for variable intervals from 3 to 7 days. These data will be used to calculate NEE light-response curves for net CO_2 uptake during the day and NEE temperature-response curves for net CO_2 release during the night. The response curve models will be driven with continuous measurements of soil temperature and photosynthetically active radiation to extrapolate up to integrated NEE for a complete growing season (Rasse et al., 2003). The gas sampling program was adjusted to increase the frequency with which NEE chambers were sampled to increase resolution for these low signal-to-noise NEE measurements, compared to the relatively stable absolute atmospheric $[CO_2]$ data when all chambers are sampled equally.

Environmental Variables

Soil temperature was measured at 5 and 15 cm depth using type-T thermocouples. Wind speed was monitored with an anemometer (O14A-L, Campbell Scientific, Logan, UT). Water level was recorded using a differential pressure transducer (PS-9805, Northwest Technologies) placed at the bottom of a 0.5 m well. All environmental data were logged on a combination of a multiplexor (AM32T, Campbell Scientific) for temperature and a datalogger (CR10X, Campbell Scientific), which were positioned remotely in the marsh to minimize analog signal degradation. Information was then relayed digitally between the marsh and main datalogger (CR1000, Campbell Scientific) using multidrop interfaces (MD485, Campbell Scientific).

RESULTS AND DISCUSSION

Treatment Application

Average daily mean $CO_2 \pm$ SE was 394 ± 1.2 ppm in ambient and 707 ± 6.0 ppm in elevated chamber atmosphere in 2007, a treatment difference of 313 ppm. The standard deviation among daily means for individual chambers averaged 21.9 and 59.0 ppm for individual ambient and elevated chambers. The variation in means between days was driven by differences in wind speed (Figure 7). High winds resulted in incursions of ambient air into elevated chambers, thereby diluting the elevated $[CO_2]$. On the other hand, stillness allowed respired CO_2 to accumulate overnight, which increased background $[CO_2]$ in ambient and elevated chambers. Because this buildup affects each treatment equally, the difference between ambient and elevated chambers persisted. However, wind incursions drove down concentrations in elevated chambers only, which decreased the difference between ambient and elevated $[CO_2]$.

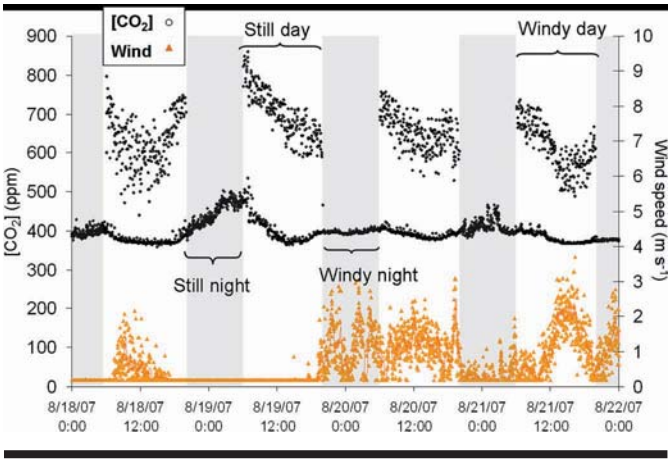

FIGURE 7. The CO_2 treatment and wind speed from four varying days in August 2007. The shaded areas represent hours of darkness when the CO_2 delivery was shut down. During those off hours, all chambers were at ambient $[CO_2]$. During still nights, ambient $[CO_2]$ approached concentrations much higher than well-mixed atmospheric $[CO_2]$ as respired CO_2 accumulated relatively near the ground.

In 2006, before chambers were equipped with frusta, ambient and elevated chambers $[CO_2]$ were 395 and 669, a difference of 274 ppm. Although the mean $[CO_2]$ could have been elevated in the chamber without adding frusta, the fluctuations with wind would have been extreme, and the expense of the additional CO_2 was deemed prohibitive.

The $[NH_4]$ in porewater was successfully increased by the N addition by a factor of 2.9, from 17 to 64 $\mu mol\ L^{-1}$ averaged over the growing season in 2006. The factor by which N addition increased porewater $[NH_4]$ was much higher early in the season and declined as growing plants took up N.

Measurement Validation: Chamber Effects

Elevation

To examine the possibility of chamber effects on elevation, we examined the measurements in the ambient CO_2,

low-N (no added N) treatment (Figure 8). The in-chamber measurements were very similar to those in the reference plots. Both sets of data revealed significant changes in elevation through time (repeated-measures MANOVA, $P < 0.05$). Most notably, all plots experienced a dip of roughly 0.8 cm in total elevation during March 2007, followed by a strong recovery. This dip was driven entirely by dynamics in the thickness of the deep zone. Compared to absolute changes in elevation (range, >1.2 cm), the differences between in-chamber and reference elevation were relatively small (range, <0.2 cm). There was a trend of a chamber effect on total elevation driven by deep zone dynamics. This effect was significant in summer 2007 but has vanished since then. The relativized root zone thickness in ambient CO_2, low-N chambers never differed from zero (t test, $P > 0.40$ for all dates), which indicated that there was not a detectable chamber effect in this stratum where we expected treatment effects to be manifested.

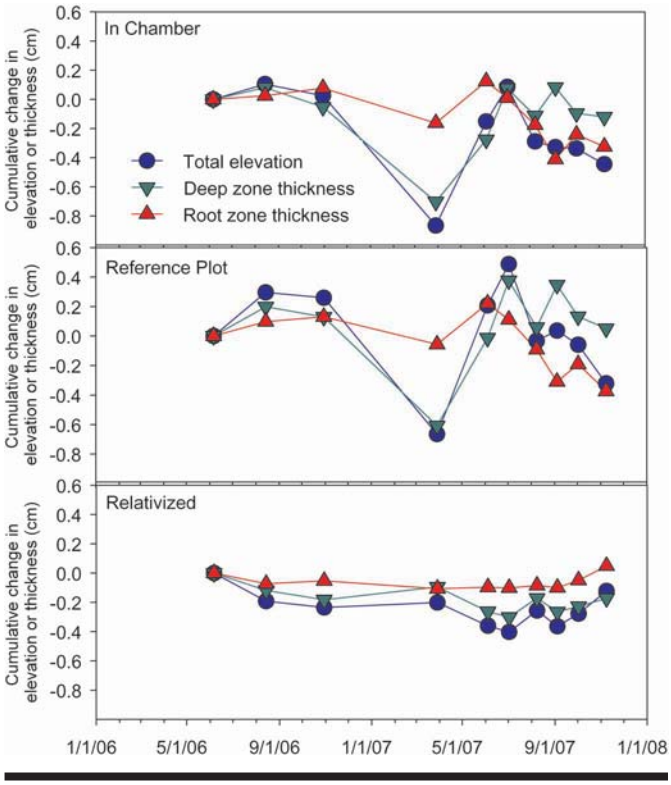

FIGURE 8. Elevation data from the five ambient CO_2, low-nitrogen (N) plots. Change in total elevation is partitioned between changes in thickness of either the deep zone or root zone. Top panel: elevation and thicknesses from inside the experimental chambers; middle panel: from the adjacent reference plots; bottom panel: difference between the in-chamber and reference measurements (relativized). There was a slight chamber effect on total elevation, driven by contraction of deep zone thickness. Root zone did not differ from zero.

Surface Accretion

One criticism of the design was that the chambers, by enclosing plots, may have excluded sediments from being deposited on the marsh surface. The difference between in-chamber and reference accretion measured with cryocores in November 2007 was small (0.058 cm) and did not differ significantly from zero (95% confidence interval: −0.18 to 0.07, $n = 20$). The treatment means also did not differ from each other (two-way ANOVA: CO_2, $P > 0.10$; N, $P > 0.10$) or from the reference plots (chamber effect: $P > 0.10$; Figure 9).

CONCLUSIONS

The design of our field experiment proved robust to a number of challenges unique to tidal salt marsh environments, including saltwater corrosion and deep tides. More importantly the chamber design allowed us to consistently elevate atmospheric CO_2. The frustum was a key feature of the chamber because it average-stabilized and raised the [CO_2] in the elevated treatment, likely resulting in saved

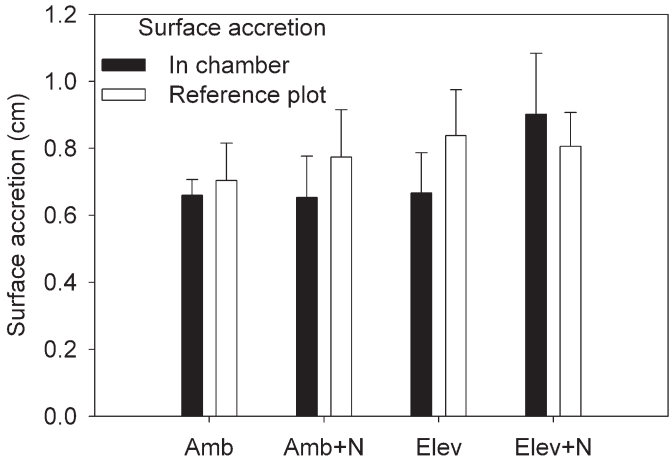

FIGURE 9. Surface accretion measured as the accumulation of matter on top of the marker horizon inside the chamber versus that outside the chamber. It was thought the chambers may exclude exogenous sediment, but there was no difference between in-chamber (black bars) and outside-chamber (reference plot, white bars) accretion rates. Amb = ambient; Elev = elevation.

CO_2. N addition yielded higher porewater N concentrations as expected, but further chemical analyses are needed for a more precise estimate of the magnitude of the N treatment. The SET design allowed for sensitive measures of soil elevation change. The chambers, perhaps by virtue of their mass, appeared to slightly depress soil elevation. However, there was no chamber effect in the root zone where the most important treatment effects are expected to occur. Further, the size of the chamber effect on elevation was small (0.2 cm; Figure 8, bottom panel) relative to the natural range of variation in those elevation parameters (1.2 cm; Figure 8, middle panel).

Acknowledgments

We thank J. Keller, G. Peresta, B. Drake, E. Sage, A. Martin, D. McKinley, S. Chapman, K. White, and N. Mudd from the Smithsonian Environmental Research Center for construction and maintenance of the field experiment. The field study was supported by the U.S. Geological Survey Global Change Research Program, U.S. Department of Energy (grant DE-FG02-97ER62458), the U.S. Department of Energy's Office of Biological and Environmental Research through the Coastal Center of the National Institutes for Climatic Change Research at Tulane University, and the Smithsonian Institution.

LITERATURE CITED

Cahoon, D. R., J. C. Lynch, and R. M. Knaus. 1996. Improved Cryogenic Coring Device for Sampling Wetland Soils. *Journal of Sedimentary Research*, 66:1025–1027.

Cahoon, D. R., J. C. Lynch, B. C. Perez, B. Segura, R. D. Holland, C. Stelly, G. Stephenson, and P. Hensel. 2002. High-Precision Measurements of Wetland Sediment Elevation: II. The Rod Surface Elevation Table. *Journal of Sedimentary Research*, 72:734–739.

Cahoon, D. R., D. J. Reed, and J. W. Day. 1995. Estimating Shallow Subsidence in Microtidal Salt Marshes of the Southeastern United States—Kaye and Barghoorn Revisited. *Marine Geology*, 128:1–9.

Drake, B. G., P. W. Leadley, W. J. Arp, D. Nassiry, and P. S. Curtis. 1989. An Open Top Chamber for Field Studies of Elevated Atmospheric CO_2 Concentration on Saltmarsh Vegetation. *Functional Ecology*, 3:363–371.

Erickson, J. E., J. P. Megonigal, G. Peresta, and B. G. Drake. 2007. Salinity and Sea Level Mediate Elevated CO_2 Effects on C_3–C_4 Plant Interactions and Tissue Nitrogen in a Chesapeake Bay Tidal Wetland. *Global Change Biology*, 13:202–215.

Rasse, D. P., J. H. Li, and B. G. Drake. 2003. Carbon Dioxide Assimilation by a Wetland Sedge Canopy Exposed to Ambient and Elevated CO_2: Measurements and Model Analysis. *Functional Ecology*, 17:222–230.

Citation:

Langley, JA, MV Sigrist, J Duls, DR Cahoon, JC Lynch and JP Megonigal (2009). Global change and marsh elevation dynamics: Experimenting where land meets sea and biology meets geology. In: Lang, MA, IG Macintyre and K Rutzler (editors). Pages 391-400 in Proceedings of the Smithsonian Marine Sciences Symposium. Contributions to the Marine Sciences, No. 38. Smithsonian Institution Scholarly Press, Washington, DC.