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In situ simulation of sea-level rise impacts on coastal wetlands using a flow-through mesocosm approach

Joseph Stachelek[a], Stephen P. Kelly[b], Fred H. Sklar[b], Carlos Coronado-Molina[b], Tiffany Troxler[c,d,e], and Laura Bauman[c]

[a]Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA; [b]South Florida Water Management District, Everglades Division, West Palm Beach, Florida; [c]Department of Biological Sciences, Florida International University, Miami, Florida; [d]Southeast Environmental Research Center (SERC), Florida International University, Miami, Florida; [e]Sea Level Solutions Center, Florida International University, Miami, Florida

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The impact of sea level rise (SLR) on coastal wetlands is dependent on the net effects of increased inundation and saltwater intrusion. The need for accurate projections of SLR impacts has motivated several experimental mesocosm studies aimed at detailed investigations on wetland biogeochemical cycling. However, the degree with which they accurately reproduce field conditions remains unknown because they have primarily been laboratory based using relatively small sediment volumes (10–200 L) treated over short time periods.

As a first step towards addressing these issues, we present a novel mesocosm device and portable methodology for long-term SLR simulation via in situ saltwater additions to relatively large sediment volumes (approximately 1,000 L). The device (chamber) consists of two interlocking polycarbonate cylinders with an internal diameter of 1.4 m. Each cylinder has holes drilled in the side to facilitate water exchange. The outer cylinder (collar) can be rotated to one of two possible positions. The first position produces alignment of the inner cylinder holes with the collar holes, whereas the second position offsets the holes to eliminate water exchange and contain salt additions (doses).

Our device design and dosing scheme produced higher porewater salinities in the sediments of treatment mesocosms relative to control mesocosm sediments. In addition, we observed low incidence of elevated porewater salinity outside of the chamber walls and no measurable salt contamination of control plots.

Widespread SLR simulations in a variety of geographical settings, whether with our proposed design or some other design, would likely help reduce some of the general uncertainties regarding the sensitivity of coastal wetlands to SLR and saltwater intrusion.

climate change | marsh | salinity | sea level

INTRODUCTION

Tide gauge records and satellite altimetry measurements clearly show evidence of global sea level rise (SLR) from the late 19th century to present (Church and White, 2011). In addition, recent modelling efforts have projected an increasing rate of global SLR into the future (Rahmstorf, 2007). One important aspect of SLR is that it is not uniform. Rather, the sea level experienced along a given coastal area is a function not only of the magnitude and acceleration of global sea levels but also their combination with regional ocean currents, teleconnection patterns, and patterns of glacial isostatic adjustment (Park and Sweet, 2015; Clark *et al.*, 1978). As a result, some locations may experience minimal SLR, whereas others could experience additional SLR of as much as 0.6 m by 2060 (Zhang *et al.*, 2011).

Another important aspect of SLR is that its potential impact on coastal wetlands is a function not only of increased hydroperiods but also of elevated salinity (Spalding and Hester, 2007). Each of these mechanisms is likely to have specific effects on biogeochemical feed-backs, carbon cycling, and wetland plant adaptation (Herbert *et al.*, 2015). In addition, there is likely to be spatial variability in the response of specific wetland processes to either increased hydroperiods, elevated salinity, or both. Overall, these knowledge gaps limit our understanding of spatial variability in SLR impacts, our ability to forecast these impacts on coastal wetlands, and our capacity to identify place-specific process thresholds (Cherry *et al.*, 2009).

Such knowledge gaps can be addressed in one of several ways. The first and most straightforward approach is passive monitoring of wetland elevation trends (e.g. Webb *et al.*, 2013). Another approach for addressing SLR knowledge gaps is simulation modelling (e.g. Jiang *et al.*, 2014). However, both passive monitoring and simulation modelling approaches lack the power to confirm specific process thresholds unless paired with a suite of additional field-based studies. A final approach, which is the subject of this study, is experimental manipulation where a set of experimental "treatment" wetland units are exposed to SLR impacts and compared with a set of experimental "controls" (e.g. Cherry *et al.*, 2015; Langley *et al.*, 2013; Spalding and Hester, 2007; Craft *et al.*, 2016; Lee *et al.*, 2016; Rasser, 2009).

These experimental manipulation approaches are especially powerful because they can provide a specific test of ecological mechanisms across many systems. In practice, these manipulations typically involve isolation of discrete sections of wetland sediment in order to directly lengthen wetland hydroperiods, elevate sediment porewater (interstitial) salinity, or a combination of the two. The physical setup for these manipulations ranges from very simple sediment filled buckets (Langley *et al.*, 2009; Rasser, 2009) to more elaborate weirs (Cherry *et al.*, 2015), tiered cylinder designs (Langley *et al.*, 2013), and electronically controlled saltwater distributions systems (Lee *et al.*, 2016).

The motivation for this study was to design an experimental manipulation approach that would alleviate two of our perceived short-comings of existing approaches. Namely, that existing approaches have primarily been laboratory based and that existing approaches have used relatively small sediment volumes (10-200 L) treated over a short time period (weeks-months). As a result, there is some question about whether or not experimental conditions in these prior studies adequately represent natural conditions and whether such short-term studies can be relied on to forecast SLR impacts which take place over the course of years to decades.

With these concerns in mind, we designed a manipulation apparatus and experimental protocol with two major design goals (1) maximize the delivery and control of experimental salt doses while (2) introducing greater realism by maintaining experimental units in situ and minimizing disturbance to the local emergent plant and periphyton communities. Here, we describe the features of our design effort relative to our two major design goals. In addition, we report on some tests of our design using a case study set in the Florida Everglades. Our case study specifically tested the hypothesis that the sediment porewater salinity of enclosed wetland units could be elevated by repeated exposure to salt treatments. This work was completed as part of a larger study to examine the response of coastal peats to saltwater intrusion and to assess whether such intrusion disrupts soil carbon balance and leads to decreased soil structural integrity (i.e., peat collapse Chambers *et al.*, 2014; Troxler *et al.*, In Press; CISRERP, 2014).

MATERIALS AND METHODS

Mesocosm Design. Our mesocosm design was inspired by earlier work done by Newman *et al.* (2004). The interior (primary) cylinder of each of mesocosm enclosure was constructed of a 0.38 cm × 0.6 m × 4.3 m sheet of clear polycarbonate formed into a 1.4 m diameter cylinder (enclosing approximately 1,000 L) using adhesive sealant (Figure 1a). Nine 10 cm holes were drilled in the side of each cylinder located 40 cm above the bottom (Figure 1b) and 30 cm above the bottom (Figure 1c) to facilitate water exchange during high and low water periods respectively (Figure 1c).

The primary cylinders were fitted with rotating polycarbonate collars (0.3 m height) having holes drilled at the same size and alignment as the primary cylinder. In effect, this gave us the ability to rotate the collar to "close" the mesocosm when delivering a salt dose and to "open" the mesocosm to facilitate water exchange. Each collar was fitted with a locking device that could be tightened to ensure minimal surface water exchange during closure (Figure 1d). The locking device was con-

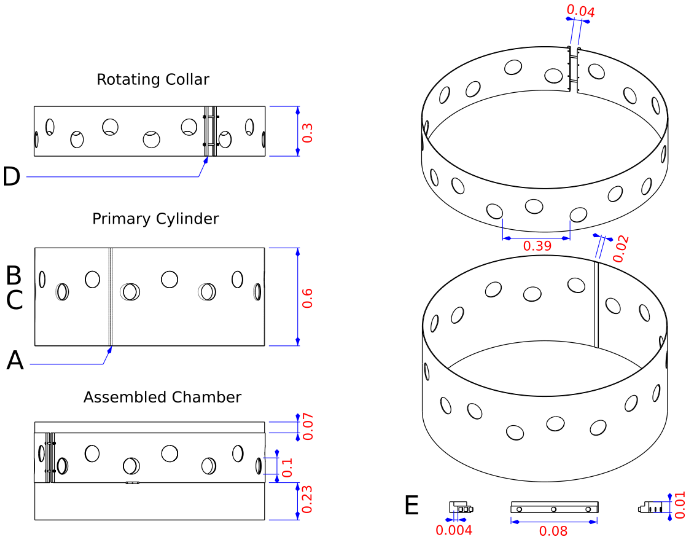

Fig. 1. Mesocosm chamber technical diagram showing (a) the primary cylinder seam, (b) upper water exchange holes, (c) lower water exchange holes, (d) collar locking device, and (e) vertical alignment brackets. Labelled units are in metres

name	description	dimensions (lwd, m)	quantity
Primary cylinder body	clear polycarbonate	4.270 * 0.60 * 0.0038	1
Primary cylinder seam	clear polycarbonate	0.020 * 0.60 * 0.0038	1
Primary cylinder seam adhesive			
Rotating collar body	clear polycarbonate	4.270 * 0.30 * 0.0038	1
Collar fastener posts	PVC or equivalent	0.015 * 0.30 * 0.0150	2
Collar fastener post attachments	M3 standoffs		
Collar fastener bolts	stainless steel, M10 x 100		2
Wingnuts	stainless steel, M10		2
Collar bracket body	PVC or similar	0.080 * 0.01 * 0.0080	3
Collar bracket attachments	M2.5 standoffs		9

Fig. 2. Parts list for construction of a single mesocosm chamber. See CAD drawings in data supplement for more detail

structed by attaching a high-density plastic (white Starboard) "handle" on either side of a vertical gap in the collar. Two sets of holes were drilled through each handle and fitted with long stainless steel bolts. The collar could then be loosened via wing nuts attached to each bolt, rotated to either the open or closed position, and re-tightened to lock into place. The vertical position of the collar was maintained via four external "brackets" attached to the exterior of the primary cylinder (Figure 1e). Each bracket was constructed of high density plastic (white Starboard) with a "groove" to hold the rotating collar.

In an effort to maximize reproducibility, we have made our CAD model used to construct Figure 1 publicly available at https://doi.org/10.5281/zenodo.1117118. These files can be opened in to inspect additional features of our design such as placement of hardware attachments. We have also included a parts list with additional details regarding dimensions, material quantities, and material dimensions of each mesocosm part (Figure 2).

Saltwater delivery protocol. We anticipate that most study designs will include "treatment" mesocosms, which are "dosed" with a saltwater treatment at regular intervals, and "control" mesocosms, which are exposed to an ambient water (fresh or brackish) treatment. The exact details surrounding delivery of these saltwater doses will be dependent on the layout and location of each study site. For example, saltwater additions in the experimental manipulations by Craft *et al.* (2016) were directly pumped from an adjacent tidal inlet. Given that such a setup is not feasible in all situations, we developed a method to deliver portable salt doses irrespective of nearby saltwater sources. Briefly, our protocol makes use of locally sourced freshwater or brackish water combined with a commercial aquarium salt mix (Instant Ocean, Blacksburg, VA, USA) prepared in 400 litre tanks (see Lee *et al.*, 2016, for a similar approach). Rather than adding an exactly prescribed saltwater dose, we devised a dosing schedule, which was based on water levels and salinity at each site, by solving the following series of mass balance equations for the volume of dose-water to be added to each mesocosm (Vb):

$$S_f = \frac{M_a + M_b}{V_a + V_b} \qquad (1)$$
$$M_b = S_b x V_b$$

where Sf represents the final salinity of the onsite (ambient) and dose water mixture, whereas Ma and Va represent the salt mass (g) and volume (L) of the ambient water within each mesocosm. Variables marked with the subscript b represent equivalent components of the dosing water volume. For example, at one of our case study sites (see below), we fixed Sb at 55 and Sf at 20. We could then solve the above set of mass balance equations by adjusting the dosing water volume (Vb). The rationale for our simple mass balance approach is that we assume our ambient-dose water mixture simple replaces existingporewater as a result of density-driven flow rather than accounting for convective diffusion.

We delivered saltwater additions to the treatment mesocosms and ambient water additions to control mesocosms from elevated boardwalks running alongside each mesocosm (Figure 2a). We used a submersible bilge-style pump (Rule, Xylem Inc., USA) to deliver doses at a maximum rate of approximately 32 l/min (500 gph). However, the actual flow rate was likely less given the distance and flow restrictions imposed by the dosing apparatus. The outlet hose was fitted with a spreader device, which was constructed by drilling holes into a short length of Polyvinyl chloride (PVC), in order to split the large output stream into twelve smaller streams. This design was intended to maximize mixing with ambient site water while minimizing scouring of sensitive benthic periphyton. Finally, emergent plants were briefly sprayed with ambient water following dosing to avoid burn from salt spray.

CASE STUDY

We tested our mesocosm design and experimental protocol in a case study at two sites within Everglades National Park, Florida, USA. One site was located within an area of freshwater wetlands, whereas the second site was located within an area of brackish wetlands. Neighbouring water level monitoring gauges indicate that the freshwater and brackish wetland sites have annual hydroperiods of approximately 312 and 184 days respectively. Patterns of inundation at each site were intermittent but not synced on a regular (e.g., tidal) cycle.

At each site, we deployed a total of 12 mesocosm chambers by inserting them approximately 15 cm into the sediment (Figure 3b). We used an unbalanced design that included 6 salt-treated mesocosms, 6 control mesocosms (treated with ambient site water), and 4 nonchamber control plots. The purpose of the nonchamber controls was to assess whether the chambers themselves influenced the experimental units over time.

We assessed the overall performance of our mesocosm design and dosing protocol at three points in time following each monthly dosing event: immediately following dosing, the following day, and 5 days post dosing. Our primary metric for assessment was the relative difference in soil porewater salinity in salt-treated chambers versus control (treated with ambient water) chambers the day after dosing. To this end, we installed three porewater wells (i.e., “sippers”) within the interior of each chamber and two porewater wells on the outside of each chamber (Figure 3c). Wells were constructed of 1-m sample tubes inserted to a depth of 15 cm. Sample tubes were constructed of flexible Tygon® tubing, sealed with teflon tape, and protected with a slotted PVC sleeve. Sampling took place for salinity, temperature, and pH via handheld probes (YSI, Inc.) by purging one length of the sipper tubing and collecting duplicate samples.

Fig. 3. Site photographs showing (a) elevated dosing boardwalks, (b) close-up of deployed mesocosm, and (c) sampling well installation

We present the results of samples collected the day after dosing because we expected that this was long enough to ensure that any flow down the sides of the installed sampling apparatus would be mixed with the surrounding porewater but not so long that porewater would be excessively diluted. We quantified postdosing salt retention/dilution in more detail as part of a pilot experiment. This pilot experiment involved outfitting a single mesocosm with a more comprehensive array of porewater wells at many different distances and sampling at a finer temporal resolution. Here we present the results of our mesocosm design and monthly dosing protocol tests over a yearly period from October 2014 to October 2015.

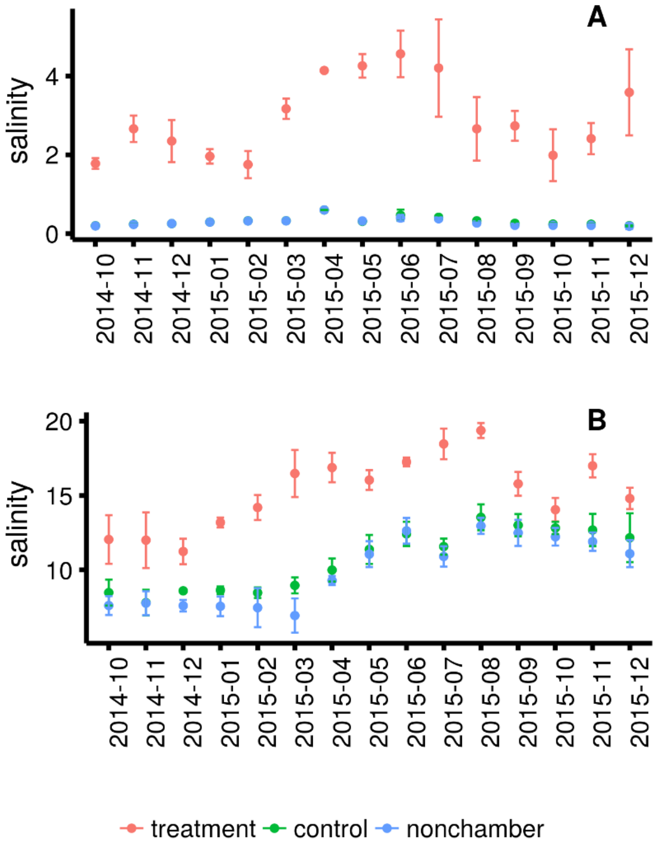

Fig. 4. Difference between treatment, control, and nonchamber-control porewater salinities at our (a) freshwater wetland site and (b) brackish wetland site

RESULTS

We found that our long-term dosing experiment was successful in raising porewater salinities above ambient (Figure 4). At the fresh-water wetland site, the salinity of the porewater was 2.9 ± 0.8 and 0.3 ± 0.1 for the treatment and control chambers respectively (Figure 4a). At the brackish wetland site, the salinity of the porewater was 15.3 ± 1.9 and 10.3 ± 1.9 for the treatment and control chambers respectively (Figure 4b). We observed few differences between our control mesocosm chambers and our nonchamber control plots (Figure 4). This suggests that the mesocosms by themselves were not directly impacting the experimental units with respect to porewater salinity. Our results were consistent with our hypothesis that indeed the porewater salinity of enclosed wetland units can be elevated by repeated exposure to salt treatments.

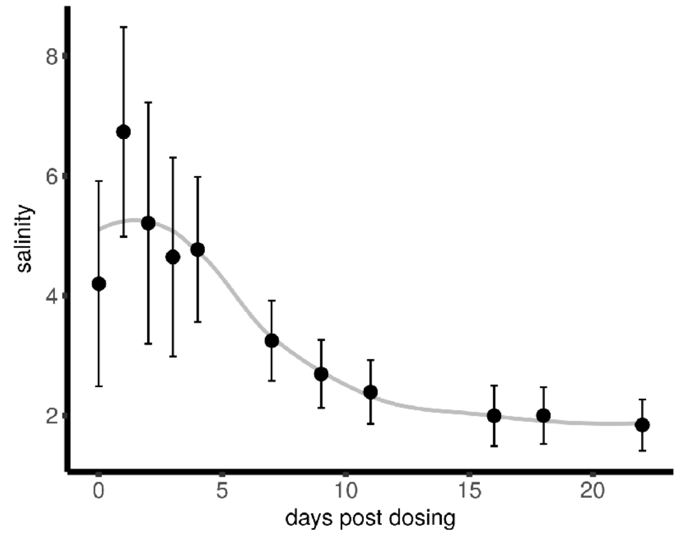

Fig. 5. Fine-scale dilution profile of salt additions to a treatment mesocosm

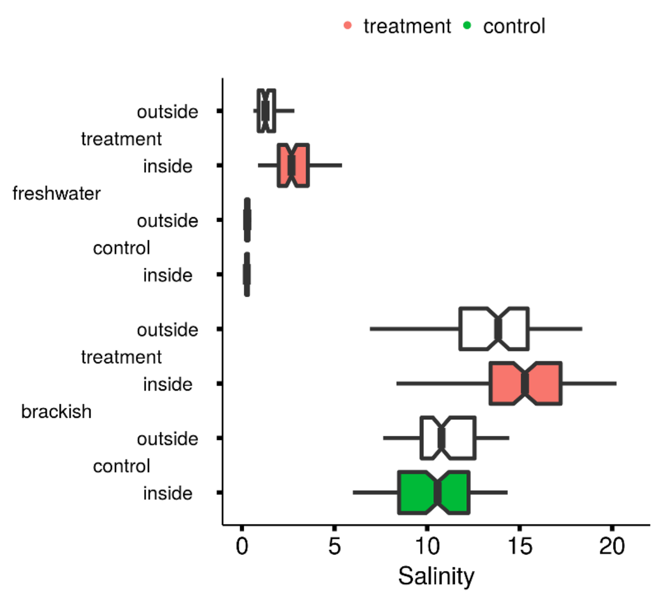

Fig. 6. Comparison between porewater salinity measured in the outside and inside-chamber sampling wells at the freshwater and brackish wetland sites. Treatment and control measurements are coloured following Figure effig:fig4

Although our design was successful in raising the porewater salinity of our treatment mesocosms over the long-term, the results of our pilot study indicate that a typical salt dose is contained within the sediment porewater of our chambers for only about 5 days, returning to approximately background levels at that point (Figure 5). Despite the fact that porewater salinities following individual salt doses remained elevated for a relatively short time period, our mesocosm design was successful in minimizing the movement of saltwater additions through the chamber walls (Figure 6). At both the freshwater and brackish wetland sites, although porewater salinity measured in the outside wells of the treatment mesocosms was slightly elevated above ambient, there was no discernable difference between the outside and inside porewater well salinity measurements in the control chambers. In contrast to anecdotal reports from previous studies, our control chambers were not contaminated with salt.

DISCUSSION

We believe our mesocosm design and experimental protocol met our design goals of (1) maximizing delivery and control over experimental salt doses and (2) introducing greater realism to experimental manipulations. In the following discussion, we identify the specific features of our design that serve to meet these design goals while contrasting our design choices with that of prior studies.

Simulation effectiveness. In our view, the primary requirement of an effective mesocosm design is that salt additions are contained within experimental treatment units as much as possible and do not "leak" into the surrounding environment. Although the performance of our design in this respect was not perfect (i.e., our mesocosms did not perfectly contain salt additions), the extent to which our mesocosms were successful in elevating porewater salinity in the treatment mesocosms suggests that our design was largely effective. For example, in our brackish wetland treatment we observed that our mesocosms maintained elevated porewater salinities around 15 approximately 24 hr after dosing when surface water salinities had been around 20. Surprisingly, few prior studies have reported porewater salinity measurements in their experimental units relative to dose (surface water) salinity. One exception is Lee *et al.* (2016) where they report adding an experimental dose with a salinity of around 10 and measuring porewater salinities of <3. In some ways, both our findings and the findings of Lee *et al.* (2016) are a consequence of an in situ design where vertical porewater movement is unbounded rather than a laboratory-based experimental design where doses are wholly contained.

We attribute some of the exceptional salt retention properties of our mesocosms (e.g., there was little evidence of elevated salinity outside experimental units) to the rotating collar feature of our design. When our rotating collars were in the closed position the water exchange holes were completely sealed. The evidence for this is that we did not observe elevated salinity in the surface water outside the chambers or contamination of control plots with salt (Figure 6). We know from anecdotal reports that mesocosms constructed using alternative designs where water exchange holes are merely plugged with rubber stoppers (e.g. Miller *et al.*, 2001) are subject to much higher probability of observing elevated salinity outside experimental units (i.e., salt leakage). It is difficult to gather information on this design aspect (potential leakage) of prior studies because it is most often not reported.

Simulation realism. In addition to faithfully containing salt additions within experimental units, we believe that a primary requirement of an effective mesocosm design is a high degree of simulation realism. To this end, our open bottom in situ design was meant to simulate slow buildup of salt in the surficial groundwater as a result of SLR while maintaining natural drainage conditions. Indeed, the pulsed nature of our salt additions meant that elevated porewater salinity was maintained for only about 5 days and was not constant. This variability contrasts with the design of many laboratory-based studies that completely isolate experimental units to impose a constant salt treatment (Brock *et al.*, 2005; Langley *et al.*, 2013). Although constantly elevated salinities may be preferable to maximize treatment effects in the short-term, we designed our experimental protocol to more realistically mimic the impact of gradual and episodic ramping of salinity over the long term (years to decades). Ultimately, our design likely comes at the cost of longer times necessary to observe a salt dose response, but we believe this is preferable to short-term simulations where experimental units are completely isolated leading to rapid salt accumulation.

Our expectation that near-term changes in SLR will cause variable and episodic increases in the salinity of shallow porewater and wetland plant root-zones is supported by several lines of observational and experimental evidence. First, in karst or low tidal systems, the response of coastal wetlands to SLR during the transition from a vegetated to open water state can be dependent on variability in seasonal groundwater- surface water exchange (Saha *et al.*, 2012). Second, Weston *et al.* (2011) describe how saltwater intrusion in wetland soils likely occurs in pulses rather than as a constant steady increase. Finally, Craft *et al.* (2016) specifically contrasted wetland responses to constant (press) and variable (pulse) salinity doses and found that although pulsed doses were transient and short-lived, there were significant impacts on the composition of the emergent plant community.

Another way in which our pulsed design maintains a high degree of simulation realism is the fact that our chambers retained a natural assemblage of flora and fauna. We view this as a substantial improvement over previous designs because biotic processes have been shown to be critical components of wetland resilience to SLR (McKee, 2011; Morris *et al.*, 2002). There are three features of our design that made this possible and set it apart from prior studies. First, our mesocosm chambers were large. Our 1000 L mesocosm chambers are much larger than most previous studies of only 10-200 L. In our study, this meant that all of our experimental units at the brackish wetland site included intact sawgrass (*Cladium jamaicense*) culms and we frequently observed fauna such as mosquitofish (*Gambusia holbrooki*) moving freely into and out of the chambers (in the open position) at the freshwater wetland site. Second, we took several steps in the experimental protocol to minimize our impact on flora and fauna including rinsing emergent plants following dosing to avoid burn from salt spray, monitoring soil redox conditions to avoid introducing severely anoxic conditions that exacerbate sulphide stress, and regulating the velocity of dose output to avoid scouring of sensitive benthic periphyton. Finally, the in situ nature of our design likely increased the realism of our simulations because it minimized physical disturbance of below-ground root material in our experimental units.

CONCLUSIONS

Ultimately, a successful SLR manipulation design requires a balance of simulation effectiveness and simulation realism. We believe that our rotating collar design gave us a unique ability to strike this balance as we were effective in containing salt additions while maintaining the conditions necessary for realistic drainage patterns and intact biotic communities.

We tested our mesocosm design and experimental protocol in two locations during our case study. Unfortunately, a comprehensive test of our design in many different settings is beyond the scope of this study. However, our design is not limited to the Everglades system. We envision that our design could be used in a variety of settings including those that experience regular daily tidal cycles. In particular, the height of our chambers could easily be increased at sites where mean high water exceeds the total installed chamber height of our design (about 0.3 m). Although regular daily tidal cycles were not a feature of our case study, water levels were below the sediment surface throughout the late spring period. During these periods we added a standard salt dose volume in proportion to an estimate of sediment pore space volume (soil porosity). In fact, the study by Craft *et al.* (2016) adopted a similar approach in a location subject to daily tidal cycles when they added salt doses only during low tide to facilitate infiltration.

We hope that our design will inspire others to initiate similar studies in a variety of geographical settings. Whether with our proposed design or some other design, a standardized methodology would likely help reduce some of the general uncertainties regarding prediction of coastal wetland sensitivity to SLR and saltwater intrusion.

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