

Testing sea-level rise impacts in tidal wetlands: a novel *in situ* approach

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Summary

1. Predictions of coastal wetland loss depend on reliable estimations of sea-level rise (SLR) and biological feedbacks to geomorphology, yet it is difficult to manipulate SLR to generate empirical data of impacts on wetland processes. Typically, data have been generated through small-scale mesocosm experiments, an approach that may not fully capture biological responses to SLR.

2. Using passive and active weirs, we manipulated inundation depths and times *in situ* and at larger spatial scales than possible in mesocosms. In June 2013, we simulated three flooding scenarios (low, intermediate and high) using passive weirs designed to increase mean low water (MLW) by approximately 8–9, 12–13 and 16–18 cm, respectively, relative to controls. In March 2014, we also conducted a proof-of-concept exercise to demonstrate that active weirs equipped with a pump can increase both MLW and mean high water (MHW), thereby achieving changes in both inundation depth and inundation time.

3. When compared to controls for the three flooding scenarios, passive weirs increased MLW in the low marsh by 9.1 ± 0.8 , 11.8 ± 1.1 and 15.65 ± 0.8 cm, respectively, and in the high marsh by 6.3 ± 3.0 , 17.0 ± 4.6 and 8.3 ± 2.5 cm, respectively. Passive weirs increased inundation time in low marsh by 0.4 ± 0.0 hd^{-1} and 2.9 ± 0.0 hd^{-1} to 24hd^{-1} in both weirs for low and intermediate flooding, respectively, but not for high flooding where the control and weirs were both inundated 24hd^{-1} . At greater elevations, however, passive weirs increased inundation time in high marsh by 0.9 ± 2.2 , 5.1 ± 4.1 and 4.0 ± 0 hd^{-1} , respectively. Weirs slowed drainage rates by 5.6 ± 1.4 , 3.8 ± 1.4 and 6.1 ± 0.1 cmh^{-1} , respectively. The active weir increased MLW by 25.4 cm, MHW by 10.5 cm and inundation time by 10.7hd^{-1} and slowed the drainage rate by 9.6cmh^{-1} .

4. Weirs can be used to increase inundation depths and times to study SLR impacts on tidal wetlands, and are advantageous because they minimize disturbance; allow for larger-scale studies within tidal wetlands; and can be maintained at little cost and effort, thereby providing more robust estimates of SLR impacts on tidal wetland processes.

Key-words: climate change, coastal wetlands, experimental manipulation, flooding, inundation depth, inundation time, mesocosms, water level

Introduction

Sea-level rise (SLR) has been accelerating since 1901, resulting in a 0.19 m increase in global mean sea level (MSL) during the last century (Church *et al.* 2013). As warming continues, the rate of SLR is expected to continue accelerating, resulting in a significant rise in global MSL by 2100 (Rahmstorf 2007; Vermeer & Rahmstorf 2009; Church *et al.* 2013). Such increases are expected to alter the frequency, depth and duration of flooding in tidal wetlands (Scavia *et al.* 2002; Church *et al.*

2013) and therefore represent an important stress to tidal wetland communities. Consequently, SLR may contribute to world-wide degradation or loss of valuable coastal habitat (Nicholls, Hoozemans & Marchand 1999; Nicholls *et al.* 2007), underscoring the need for management strategies to mitigate climate-related threats to tidal wetlands.

Predictions of coastal wetland land loss depend on reliable estimations of SLR, as well as an understanding of biological feedbacks to geomorphology. Models predicting significant changes in wetland distribution or high rates of land loss in response to SLR often assume coastal landscapes are static (Blum & Roberts 2009; Craft *et al.* 2009; Glick *et al.* 2013), neglecting the role of nonlinear feedbacks for elevation maintenance. Excluding these potential feedbacks, or assuming they are spatio-temporally consistent, may result in overestimates

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of future land loss (Kirwan & Guntenspergen 2009). Conversely, numerical models that include nonlinear feedbacks suggest there are scenarios whereby tidal wetlands can avoid submergence (Morris *et al.* 2002; Kirwan & Murray 2007; Kirwan *et al.* 2010; Schile *et al.* 2014). Effective management strategies to mitigate climate risks and maximize wetland stability depend on understanding mechanisms controlling these feedbacks, and potential changes in response to climate change and other impacts.

Process-based experiments that manipulate SLR along with other factors are necessary to identify mechanisms controlling nonlinear feedbacks and to improve model predictions (Evans 2012). Experimentally manipulating SLR in tidal wetlands typically has been limited to smaller-scale (<0.5 m²) mesocosm experiments using transplanted wetland material exposed to different inundation depths and times, such as those carried out in glasshouses (e.g. Spalding & Hester 2007; Cherry, McKee & Grace 2009) or ‘marsh organs’ (described in Morris 2007). While permitting controlled experiments in which multiple factors can be manipulated, mesocosm experiments only capture processes occurring at smaller spatial scales and may create artefacts not experienced *in situ*, including disturbances during sod extraction and subsequent changes to hydrology, biogeochemistry or biological communities (e.g. movement and abundance of fauna). They also do not permit measurement of upslope migration by plants in response to SLR. Therefore, mesocosm studies may not provide a complete picture of biological responses to changing climate.

Ideally, larger-scale, *in situ* manipulations of SLR would complement information gained from mesocosm studies. Prior successful attempts to manipulate hydrology or salinity *in situ* include pumping additional water onto tidal marsh plots (Tolley & Christian 1999; Miller, Neubauer & Anderson 2001), repeatedly adding fresh or brackish water to freshwater tidal marsh plots (Neubauer 2013) and repeatedly adding sea salt to saltmarsh plots (Silliman *et al.* 2005). Others have utilized pumps to deliver sediment-water slurries in freshwater marsh plots (e.g. Graham & Mendelssohn 2013). Collectively, these studies suggest that field-based approaches that pump or otherwise add water or salt to tidal wetlands can be conducted at larger spatial scales (e.g. up to 12 m²) and have the potential to improve understanding of biological responses to SLR.

We developed a new approach using passive and active weirs to experimentally manipulate inundation depth and time *in situ* and at larger spatial scales than possible with mesocosms. The passive approach increases mean low water (MLW) without affecting mean high water (MHW), thereby reducing tidal amplitude, while the active approach utilizes pumps to increase both MLW and MHW, thereby maintaining tidal amplitude. By manipulating these aspects of water level, we can simulate the effects of increased inundation depth and time on communities and ecosystem processes. Because weirs can be installed to span elevation gradients and tidal ranges, they may also capture a greater range of possible responses to SLR to address critical gaps in our understanding of wetland stability (Kirwan & Megonigal 2013). Manipulating inundation depth and time using our weir approach

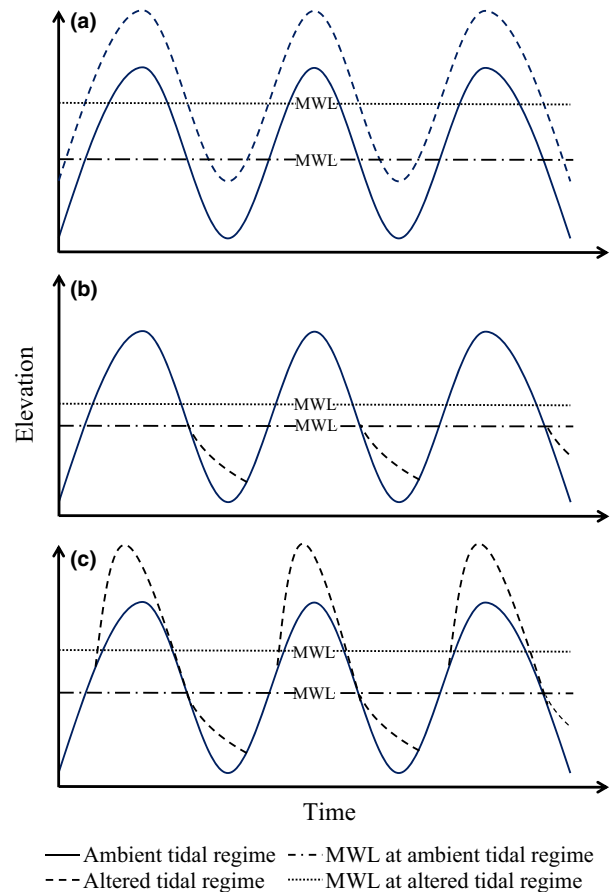


Fig. 1. Conceptual figure depicting how (a) sea-level rise, (b) the passive weir design and (c) the active weir design affect inundation compared to ambient conditions. Horizontal lines depict mean water levels (MWLs) for ambient or altered tidal regimes.

may provide a more realistic assessment of SLR impacts and generate unprecedented empirical data for predictive models of tidal wetland vulnerability.

Materials and methods

DESIGN CONCEPT

Sea-level rise is expected to result in changes to the frequency, depth and duration of flooding in tidal wetlands (Fig. 1a; Scavia *et al.* 2002; Church *et al.* 2013). Experimental weirs were designed to mimic aspects of SLR by either increasing inundation depth at low tide (passive approach) or increasing inundation depths at both low and high tides (active approach), as well as increasing inundation times and slowing drainage rates during ebb tides.

Passive weirs slow water drainage and retain more water for longer during ebb tides, resulting in greater MLW levels with no effect on MHW (Fig. 1b). Passive weirs are constructed with three walls (open on the upslope end), including one front wall parallel to shore and two sidewalls perpendicular to shore. Walls should be constructed using a sturdy, inert material that can withstand environmental conditions (e.g. UV, wave action) and pressure exerted by added water. Valves in the front wall permit filling during flood tides at a rate similar to ambient conditions, but slow the rate of drainage during ebb tides,

thereby enhancing both inundation depth and time. The effects of this manipulation should be observed throughout the plot, but the extent of inundation will vary based on changes in surface elevation within the weir footprint (i.e. higher elevations flooded to a lesser extent and for less time) and can be manipulated by adjusting wall heights and drainage valve position relative to the soil surface.

Because SLR will also increase MHW, passive weirs can be modified to include pumping mechanisms that increase MHW. These active weirs, so termed because water levels are achieved using a pump, manipulate MLW levels and drainage rates during ebb tides as in passive weirs, but also add water at high tide, thereby increasing inundation depth and time without changing tidal amplitude (Fig. 1c). As with passive weirs, the height of drainage valves determines MLW and can be achieved without active manipulation. The specific height and number of walls will depend on the site's tidal range, elevation gradient and targeted MHW levels.

In macrotidal systems or when simulating greater SLR, relatively tall wall heights may be necessary, making wall material selection and installation depth important considerations to ensure weir stability. When the elevation gradient within a weir is steep and wall heights exceed desired MHW, active weirs can be constructed with three walls, as in the passive weir design. Otherwise, four walls will be required to achieve increased inundation depths at high tide. For both active and passive weirs, the length and height of weir walls, position and capacity of drainage valves, and overall footprint can be tailored to suit local conditions and experimental designs. Specific designs for the weirs used in this study are detailed below.

SITE DESCRIPTION

This study was conducted in Weeks Bay National Estuarine Research Reserve (NERR) in Baldwin County, AL, USA, which encompasses 26 km² of tidal and forested wetlands. Weeks Bay experiences diurnal, microtides (0.3–0.5 m) that are sensitive to meteorological effects (e.g. winds). Within the NERR, we identified three locations for marsh restoration beginning in December 2012. We constructed the marsh platform by adding *c.* 10–30 cm of clay to previously eroded shoreline, over which we added 20–30 cm of dense, mineral topsoil (OM content: 4.66 ± 0.21%; bulk density: 1.26 ± 0.03 gm⁻³; porosity: 50.77 ± 1.23%). Each platform was approximately 20 m long and 3 m wide. Coconut coir logs (3 m long, 0.3–0.5 m diameter) were positioned along the marsh edge to prevent erosion. In February 2013, intact sods of soil and vegetation were collected from a nearby marsh within the Weeks Bay NERR and transplanted into each marsh. We installed experimental weirs once vegetation was well established (June 2013). While we installed weirs in restored marshes, the approach is also suitable for natural tidal wetlands.

PASSIVE WEIR DESIGN

To simulate greater inundation depths and times, we constructed passive weirs that retained water during low tide, increasing MLW and inundation time relative to controls (Fig. 2). Weirs consisted of three walls inserted into the sediment, with the upland side open to permit upslope migration of vegetation and movement of fauna (Fig. 3a). The front weir wall was oriented parallel to the shore along the edge of the water, while sidewalls were oriented perpendicular to shore. Weirs were constructed of inert, waterproof panels thick enough to withstand pressure from water when full. In this case, we used 1.27-cm-thick Plas-Tex panels made of recycled polyethylene and polypropylene mixed with

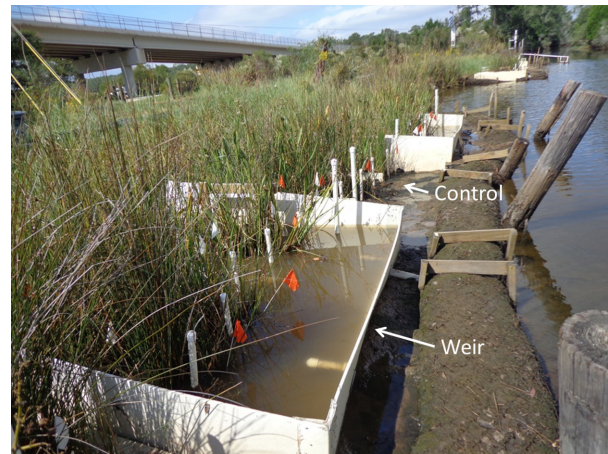


Fig. 2. Weirs installed in restored tidal marsh at Weeks Bay National Estuarine Research Reserve in Alabama, USA.

calcium carbonate (Plas-Tex; Parkland Plastics, Inc., Middlebury, IN, USA). In this study, all walls were 0.6 m tall; sidewalls were 2.4 m long; and front walls were 2.4–3 m long, extended when necessary by overlapping panels using silicone caulk and stainless steel screws (Fig. 3).

To accommodate water flow valves (described below), two circular holes (7.6 cm diameter) were drilled in the face of the front weir wall using a bimetal hole saw. Corners were secured using L-shaped braces made by cutting hollow, vinyl fence posts (10 cm × 10 cm) lengthwise along opposite corners. Braces were attached to the inside and outside of each corner using silicone and stainless steel screws, washers and nuts. Weirs were transported to the marshes for installation *c.* 24 h after assembly.

Once on site, weirs were positioned for installation, leaving a buffer zone of *c.* 0.5 m between the front weir wall and vegetation. Installation depths depend on sediment porosity, which affects drainage rates, with the minimum depth of installation determined by sediment stability. In this study, walls were installed *c.* 20–30 cm deep by a team of 6–8 people using sledgehammers (Appendix S1). Hammering was performed on square pieces of Plas-Tex panelling (*c.* 30 × 30 cm) atop wall edges to avoid damaging weirs.

Tidal flow was regulated using two valves installed after weirs were in position. Water flow valves consisted of 7.6-cm-diameter caulkless shower drains fitted into pre-drilled holes in the front weir wall, through which 5-cm-diameter PVC pipes were inserted (Appendix S2). One pipe was fitted with an in-line check valve to allow water entry during flood tides but to prevent drainage during ebb tides. The second pipe was covered with a 5-cm PVC end cap, and had two, 0.3-cm-diameter holes water drainage rates during ebb tides. Drainage holes also permitted some water to enter during flood tides, but most water entered through the in-line check valve. Together, these valves allowed water to enter the weir at the natural tidal rate, but slowed the drainage rate during ebb tides. Once the water level inside the weirs dropped below the valve level, drainage stopped. Thus, the maximum inundation depth during low tide, or MLW, was determined by valve heights relative to soil surface. The number and size of drainage holes can be changed to achieve desired drainage rates, and valve heights can be changed to achieve desired inundation depths.

To measure changes in water level over time, wells containing water level recorders were installed inside weirs and adjacent controls. Each well contained a water level recorder (Levelogger & Barologger Model 3001 Edge F15/M5; Solinst Canada Ltd, Georgetown, ON, Canada) that measured changes in absolute pressure at 15-min intervals. Data

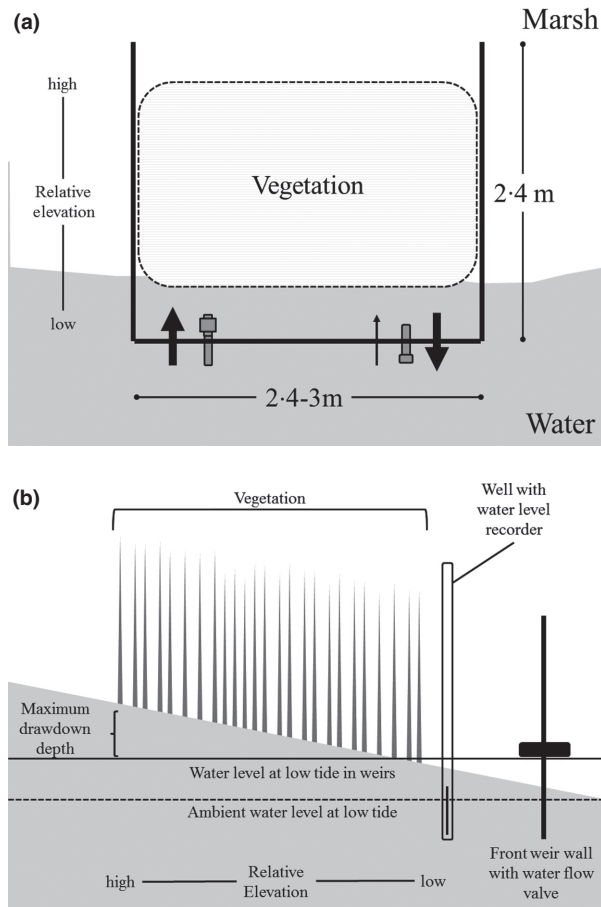


Fig. 3. Weir designs. (a) Plan view showing three walls and an open end to permit upslope migration of vegetation. Two valves inserted through the front wall controlled water movement as indicated by arrows; arrow thickness indicates relative volume of water flow through the in-line check valve and drainage valve on the left and right, respectively. (b) Side view showing that flooding of vegetation varied with relative elevation and valve height, with maximum inundation occurring at lower elevations. Water level recorders were located within wells placed at the low-marsh edge, and thus, captured maximum flooding effects on vegetation.

were compensated for local barometric pressure and converted to water level (m). The top of the water level recorder was positioned flush with the soil surface so that the pressure transducer was located 14 cm below the surface. Wells were positioned at the low-elevation end of vegetation (Fig. 3b), and as such, reflected maximum inundation depth and time experienced by vegetation. Inundation depth and time decreased with increasing marsh elevation, such that high-marsh locations within weirs typically did not remain inundated during low tide. A slideshow video of the passive weir approach is available in Appendix S3.

ACTIVE WEIR DESIGN

We also conducted a proof-of-concept exercise using active weirs to increase both MLW and MHW, thereby changing inundation depth and time without altering tidal amplitude. The active weir was a modified version of the passive weir design, but included a fourth, upland (i.e. back) wall to test the pumping mechanisms in a smaller footprint (Fig. 4). Dimensions for the active weir were 0.6 m wide \times 1.2 m long \times 0.6 m tall to accommodate higher water levels.

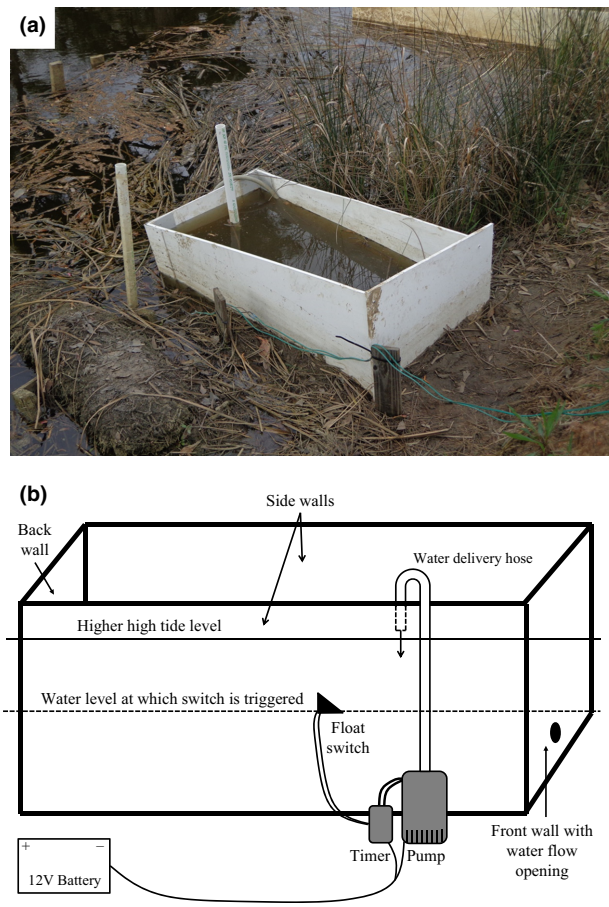


Fig. 4. Active weir design to achieve higher MHW levels (a) installed at Weeks Bay National Estuarine Research Reserve, Alabama, USA, and modified to include (b) four walls and a battery-operated pump.

Active weir assembly was the same as with passive weirs, except that the active weir had only one 0.16-cm-diameter hole located at a water level of 0.1 m rather than having two water flow valves. To pump water into the active weir, a battery-powered float switch, timer and bilge pump system was used. This system was powered by a standard 12V deep-cycle marine battery. A float switch (Johnson Pumps of America 26014 Marine Automatic Float Switch, SPX, Charlotte, NC, USA) was mounted outside the active weir at a height where it activated the timer module (ELK-960 Delay Timer; ELK Products, Hildebran, NC, USA) when the rising tide reached a water level of 0.15 m. The timer activated a 1360-lh⁻¹ bilge pump (Rule 24 Marine Rule 360 Marine Bilge Pump, Rule Industries, www.ruleindustries.com) attached to a 1.9-cm-diameter garden hose with its terminal end mounted within the weir. This pump was set to run for 4 min per activation, as regulated by timer settings, thereby filling the weir to a depth of 0.375 m.

WEIR COST AND MAINTENANCE

Expense and time associated with constructing, installing and maintaining weirs were relatively low. For the weirs described here, the cost was approximately US \$260 per weir, plus US \$250 in one-time tool costs (Appendix S4). Except for the plastic panels, all materials were available off-the-shelf from local stores. For passive weirs, maintenance requirements were minimal, primarily consisting of periodic clearing of drainage holes to maintain consistent flow rates. An additional US

\$180 was needed for the battery, timer, float switch, bilge pump, wiring and connectors to create the active weir. The only additional maintenance consideration for the active weir was charging the battery weekly and installing a waterproof housing.

ASSESSING WEIR PERFORMANCE

Each study marsh included three controls, three passive weirs and three weir controls. Controls were unmanipulated areas of restored marsh in which the tidal regime was unaltered. Passive weirs were installed so that the front wall was situated between the coir logs and marsh vegetation. A weir control was also installed adjacent to each weir by adding 0.6 m tall × 2.4 m long sidewalls that remained open on both ends. The purpose of the weir control was to test the effect of the lateral walls on water retention. Each marsh was randomly assigned to a low-, intermediate- or high-flooding scenario, which were achieved by positioning the top of the drainage valves at 12, 15 and 18 cm above the marsh surface, respectively, to increase MLW relative to controls by 8–9, 12–13 and 16–18 cm, respectively.

Within each marsh, one control and two passive weirs were equipped with water level recorders. In the high-flooding scenario, a weir control was also equipped with a water level recorder, for a total of 10 recorders. Water level was recorded at 15-min intervals from 28 June to 26 July 2013. For each flooding scenario, we compared water levels between weirs and the control, focusing on the ability of passive weirs to increase inundation depth and time. Because elevations varied between and within plots, actual surface elevations of water level recorders, as well as five locations along both the low- and high-marsh edges, were documented using a GPS real-time kinetic (RTK) device connected to a continuously operating reference station (CORS) referenced to NAVD88 vertical datum. RTK measurements were not possible in the low-flooding scenario or active weir because of tree coverage, and as such, elevations relative to the soil surface (0 cm) are presented. Relative elevation change within the low-flooding plots was estimated by measuring the difference in water heights above the soil surface at five low-marsh and five high-marsh locations within a 1-h period. From this and the NAVD88 elevations, elevation gradients encompassing the vegetated area were determined (Table 1). Elevation gradients were steepest in the low-flooding scenario, and generally lowest in the intermediate-flooding scenario. In the control and two weirs of the intermediate-flooding scenario, actual surface elevations (NAVD88) were 12.4 ± 1.1 , 9.1 ± 0.8 and 16.7 ± 0.7 cm, respectively, in the low marsh, and 22.2 ± 0.6 , 23.8 ± 1.0 and 22.9 ± 1.4 , respectively, in the high marsh. In the control, two weirs and weir control of the high-flooding scenario, actual surface elevations (NAVD88) were 11.6 ± 1.1 , 13.1 ± 1.3 , 14.1 ± 1.4 and 14.6 cm, respectively, in the low marsh, and 23.4 ± 0.3 , 25.0 ± 1.1 , 27.8 ± 1.2 and 28.2 cm, respectively, in the high marsh.

For the 28-day sampling period, we determined the monthly low, mean and high water levels in each of the 10 sampling locations by arithmetic mean. We calculated the mean inundation time by averaging the number of hours per day that the marsh surface was inundated over the 28-day sampling period. Monthly drainage rates during the ebb tide were calculated by averaging the daily changes in water level between high and low tide. A similar approach was taken to determine the monthly MLW, mean water level, MHW, inundation time and drainage rate within the active weir from 19 to 27 March 2014 (8 days). These calculations provided a direct estimate of changes in flooding occurring at the low-marsh location where the water level recorder was positioned. The difference in elevation between low and high marsh within each plot was then used to estimate water levels and inundation

Table 1. Monthly mean low water (MLW), mean water level (MWL), mean high water (MHW) and mean inundation time for low-marsh and high-marsh locations, and mean monthly drainage rate during ebb tide, for the low-, intermediate- and high-flooding scenarios during the 28-day study period. Mean elevation gradients, expressed as the difference in elevation between low-marsh and high-marsh locations ($n = 5$ for control and weir plots; $n = 1$ for weir control), are also provided for all flooding scenarios. For low flooding, values reflect relative changes in elevation and are not referenced to a tidal datum; for intermediate and high flooding, values reflect actual changes in surface elevation (NAVD88 cm)

	Flooding Level					
	Low		Intermediate		High	
	Low Marsh	High Marsh	Low Marsh	High Marsh	Low Marsh	High Marsh
MLW (cm)						
Control	7.8	-31.2	10.7	-0.47	19.4	8.4
Weir 1	16.1	-27.9	25.6	12.0	30.1	14.2
Weir 2	17.6	-21.9	27.1	21.1	32.3	19.1
Weir Control					15.4	1.8
MWL (cm)						
Control	30.1	-8.9	31.0	19.8	39.9	28.8
Weir 1	28.8	-15.2	38.7	25.1	39.8	23.9
Weir 2	34.5	-5.0	38.3	32.3	42.6	29.4
Weir Control					34.2	20.6
MHW (cm)						
Control	50.5	11.5	50.6	39.4	59.3	48.2
Weir 1	46.4	2.4	55.6	42.0	54.6	38.7
Weir 2	53.6	14.1	54.8	48.8	58.5	45.2
Weir Control					53.3	39.7
Inundation (h d⁻¹)						
Control	23.6	5.1	21.1	9.6	24	20.0
Weir 1	24	3.8	24	10.5	24	24
Weir 2	24	8.1	24	18.8	24	24
Weir Control					21	15
Rate (cm h⁻¹)						
Control	11.2		10.2		10.4	
Weir 1	4.3		9.5		4.3	
Weir 2	7.0		3.4		4.4	
Weir Control					8.7	
Elevation Gradient (cm)						
Control	39.0 ± 4.2		9.8 ± 0.7		11.8 ± 1.0	
Weir 1	44.0 ± 7.3		14.6 ± 1.0		11.9 ± 1.0	
Weir 2	39.5 ± 4.4		6.2 ± 1.6		13.7 ± 1.6	
Weir Control					13.6	

times for the upper extent of the vegetated area, or high marsh, in each plot.

To test the null hypothesis that MLW, mean water level, MHW, inundation time and drainage rate were not influenced by weirs, we performed separate one-sample *t*-tests comparing weir means ($n = 2$) against the control ($n = 1$) in each flooding scenario, and against the weir control ($n = 1$) in the high-flooding scenario. Significance is reported at both $\alpha = 0.05$ and 0.10 levels. All analyses were performed in JMP v10.0 (SAS Institute, Cary, NC, USA).

Results

Relative to controls, passive weirs generally increased water levels and inundation times and slowed drainage rates of the vegetated marsh, despite differences in elevation between weirs and control and between low and high marsh (Fig. 5; Table 1).

In low marsh, passive weirs increased MLW by 9.1 ± 0.8 , 11.8 ± 1.1 and 15.65 ± 0.8 cm, respectively. By retaining water during low tide, passive weirs significantly increased low-marsh MLW for all flooding scenarios ($P = 0.05$, $P = 0.03$ and $P = 0.06$, respectively) with minimal increases in MHW (Fig. 5; Table 1). These increases in low-marsh MLW

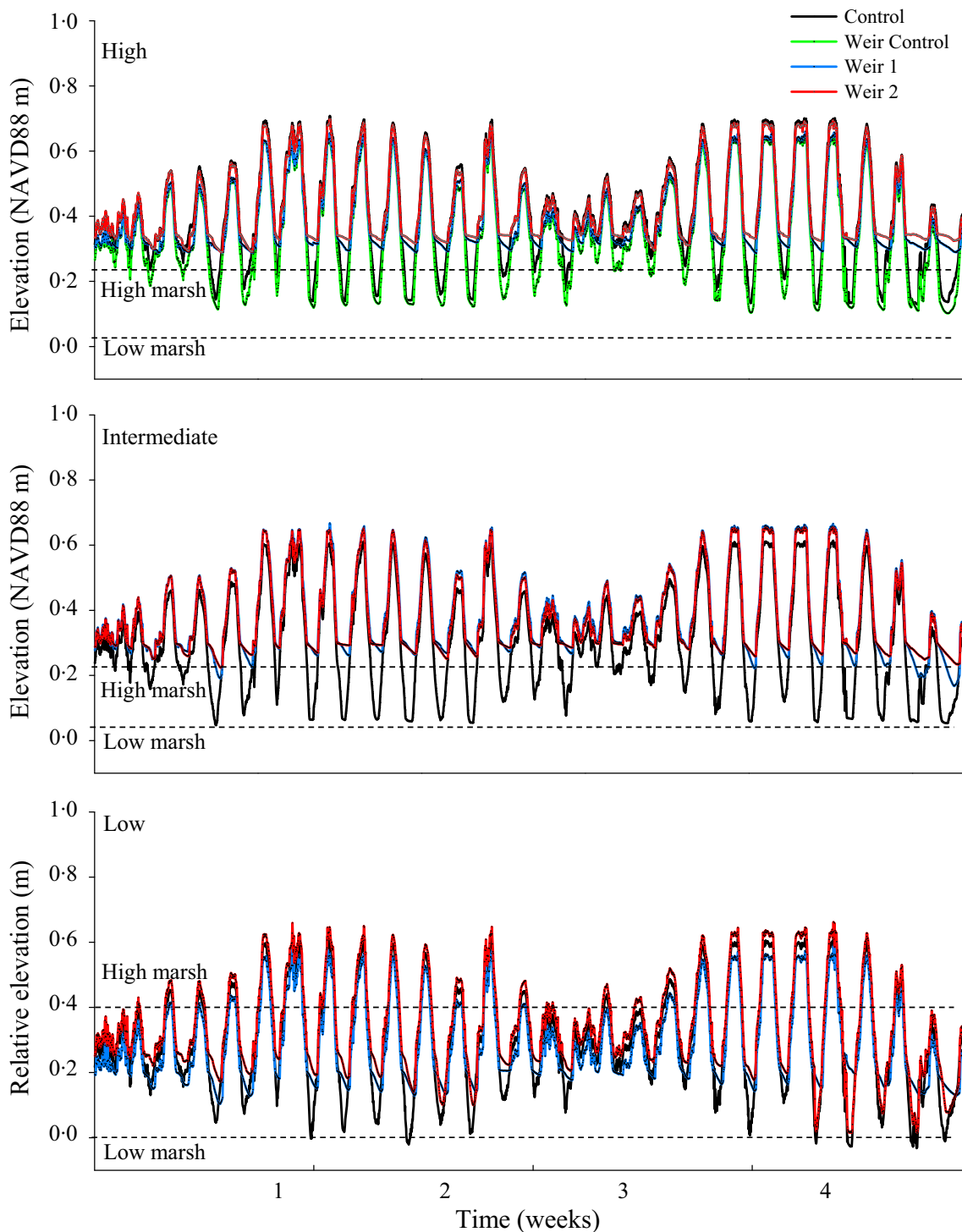


Fig. 5. Change in inundation elevation (NAVD88 m) relative to the soil surface from 28 June to 26 July 2013 in controls, a weir control and weirs for the low-, intermediate- and high-flooding scenarios. Horizontal lines delineate marsh surface elevations at the low- and high-marsh extremes within each flooding scenario. Relative elevation (m) is presented for low flooding because NAVD88 elevations were not available.

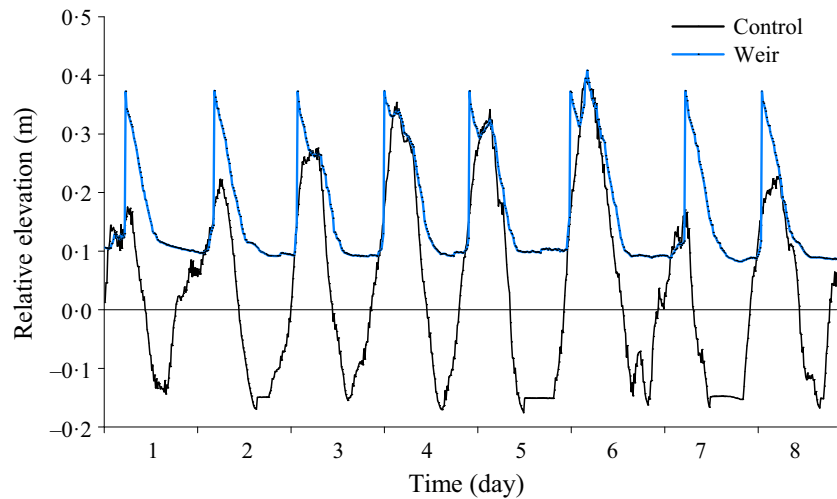


Fig. 6. Change in inundation elevation (m) relative to the soil surface (0 m) from 19 to 27 March 2014 in a control and active weir with 0.6-m-tall walls to achieve greater mean high water (MHW) level relative to the control. MHW levels were similar in the weir and control on days 4–6 when rain events resulted in tides that overtopped weir walls, a factor that can be controlled using taller walls.

led to a significant increase in mean water level for the intermediate-flooding scenario ($P = 0.02$), but not for the low- or high-flooding scenarios ($P > 0.50$ for both; Fig. 5; Table 1). Passive weirs significantly increased inundation times by 0.4 ± 0.0 and 2.9 ± 0.0 hd^{-1} (or to 24hd^{-1} in both weirs) for low and intermediate flooding ($P = 0.008$ and $P = 0.001$), respectively, but not for high flooding where all plots were inundated 24hd^{-1} . While weirs slowed drainage rates by 5.6 ± 1.4 , 3.8 ± 1.4 and 6.1 ± 0.1 cmh^{-1} , respectively, these reductions were only significant in the high-flooding scenario ($P = 0.01$). In high marsh, weir effects on MLW and inundation time were reduced, increasing MLW by 6.3 ± 3.0 , 17.0 ± 4.6 and 8.3 ± 2.5 cm, respectively, and inundation time by 0.9 ± 2.2 , 5.1 ± 4.1 and 4.0 ± 0 hd^{-1} , respectively. However, these increases were not significant when compared to the controls ($P > 0.10$ for all scenarios).

Within each restored marsh, the two passive weirs performed most consistently over time in the high-flooding scenario, while in the low and intermediate scenarios, weir effects were less reliable over the month (Fig. 5, Table 1). In the high-flooding scenario, the magnitude of MLW increase was consistent between weirs over time, but not in the low- and intermediate-flooding scenarios in which one weir retained more water than the other during parts of the month. The extent to which increases in MLW influenced mean water level differed among scenarios. With low and high flooding, mean water level was similar among weirs and the control, whereas it increased by

7.5 ± 0.2 cm in weirs of the intermediate-flooding scenario. Despite these variations in weir performance, the main effect of passive weirs was to increase the depth and duration of flooding during low tide, regardless of differences in surface elevation among plots.

We noted only minor differences in water levels, inundation times and drainage rates between the control and weir control, with the weir control having slightly lower water levels and inundation times (Fig. 5; Table 1). These differences likely arose because the weir control was 3 cm higher in elevation than the control. Differences between the weir control and the weirs, however, were similar to those observed between the control and weirs, with the passive weirs significantly increasing MWL and inundation time ($P = 0.04$ and $P = 0.001$, respectively), and significantly slowing drainage rate ($P = 0.007$), relative to the weir control (Table 1).

We also monitored water levels, inundation times and drainage rates in an active weir compared to an unmanipulated control (Fig. 6). The active weir increased MLW by 25.4 cm, mean water level by 16.1 cm, MHW by 10.5 cm and inundation time by 10.7hd^{-1} , and it slowed drainage by 9.6cmh^{-1} (Table 2). These results suggest that the active weir can be modified to accommodate different SLR scenarios and larger experimental footprints, and to provide greater regulation of water level manipulations over time.

Discussion

Sea-level rise is expected to alter the frequency, depth and duration of flooding in tidal wetlands (Scavia *et al.* 2002; Church *et al.* 2013) and, as a result, represents an important stress to many tidal wetland communities. Flooding contributes to the formation of anaerobic conditions and root oxygen deficits in wetland soils, which can alter biogeochemical transformations, reduce plant productivity and ultimately influence biological feedbacks to geomorphology (DeLaune & Pezeshki 1991; Morris *et al.* 2002; Spalding & Hester 2007). To mitigate these impacts, it is necessary to identify mechanisms controlling biological responses to different

Table 2. Mean low water (MLW), mean water level (MWL), mean high water (MHW) and drainage rate during ebb tide relative to the marsh surface (0 cm) in the control and active weir over the 8-day study period

	Control	Weir
MLW (cm)	-16.4	9.0
MWL (cm)	0.7	16.8
MHW (cm)	27.2	37.7
Inundation (hd^{-1})	13.3	24
Rate (cm h^{-1})	11.9	2.3

inundation scenarios. Through the use of passive weirs, we increased inundation depth and time and slowed the drainage rate during ebb tides, which increased plant submergence and soil waterlogging as would be expected with SLR. Thus, passive weirs provided a means to manipulate inundation depth or time *in situ* and to simulate SLR effects on wetland processes.

Variation in passive weir performance resulted in different magnitudes of inundation depth and time in some flooding scenarios, but not in others. This discrepancy was most apparent in the low-flooding scenario, and likely arose due to changes in marsh platform elevation following construction. Following weir installation but prior to the study, the marsh surface in the low-flooding scenario subsided, resulting in a steep elevation gradient between low and high marsh. If subsidence resulted in an increase in valve heights relative to the surface without affecting water retention, inundation depth and time were greater, as with weir 1. If subsidence resulted in a leak as walls moved relative to the surface, inundation depth and time were lower and more similar to the control, as with weir 2. Thus, it is important to insert weirs deep enough into compacted sediments to prevent leaking and with valves at similar heights relative to the soil surface to avoid differences in inundation depth. The risk of leakage would likely be reduced in natural or older restored wetlands where sediments are more consolidated. When the desired inundation level is achieved, weirs can be used to effectively increase MLW and simulate anticipated increases in flooding with SLR.

However, SLR will also increase flooding at high tide, thereby increasing inundation depth and time without reducing tidal amplitude (Fig. 1a). Achieving higher MHW levels may be important for understanding some wetland processes, including sedimentation and vertical accretion (Morris *et al.* 2002) or impacts on plant physiology (Pezeshki, Pardue & DeLaune 1996b; Pezeshki *et al.* 1996a; Li, Yang & Li 2007). Recognizing this, we demonstrated that active weirs can achieve higher MLW and MHW levels, thereby increasing inundation time. While this proof-of-concept test was limited in temporal and spatial extent, the design can be modified and scaled up, as has been demonstrated in other studies that utilized pumps to add water in marshes (Tolley & Christian 1999; Miller, Neubauer & Anderson 2001). Thus, active weirs are a viable option to more realistically simulate SLR impacts on tidal wetlands when passive weirs are insufficient, and may offer greater control to minimize interweir variability or target specific SLR scenarios.

Process-based studies designed to identify mechanisms controlling biological responses to SLR typically have used mesocosms (Spalding & Hester 2007; Cherry, McKee & Grace 2009). Unlike mesocosms, however, passive and active weirs are installed directly into intact, natural or restored wetlands, thereby minimizing disturbance to the rhizosphere and permitting experimentation at larger spatial scales. Various levels of flooding depth and duration can be achieved by altering the height of the valves relative to soil surface or by adding pumps to achieve higher MHW. Furthermore, three-wall weir instal-

lations permit upslope migration of plants in response to increased submergence, as well as movement of fauna into and out of the weir. Finally, both passive and active weirs can be constructed and maintained at relatively low cost and effort. These advantages suggest that weirs may provide more robust estimates of SLR impacts on tidal wetland processes, especially those arising from increased flooding of the rhizosphere and soil surface.

Utilization of weirs in other tidal wetlands may require modifications to accommodate differences in tidal range, elevation gradient, plant community composition or other biophysical factors. In meso- or macrotidal systems, wall heights or lengths may need to be greater to achieve desired levels of flooding, especially if higher MHW levels are desired, and the number and size of inflow and outflow valves or the pumping capacity may need to be altered to achieve desired rates or durations of water flow. With accurate tide and topographic information, weirs can be modified by varying wall lengths or valve heights relative to soil surface to create different flooding scenarios along a wetland elevation gradient. As our study demonstrated, the extent and magnitude of inundation depth and time can vary within weirs as elevation increases from the low to high marsh, making it important to know the elevation gradient encompassed by the weir. Weir size and installation may need to change depending on dominant vegetation or sediment type. When working in mangroves or other forested wetlands, for example, weirs should be large enough to accommodate larger individual plants. Finally, the presence of extensive root systems or woody debris may require trenching for weir installation.

As with other experimental manipulations, it is necessary to consider potential artefacts that could influence study outcomes. In this case, weir controls are required to evaluate wall effects on variables of interest. Weirs may dissipate wind or wave energy, thereby altering dissolved oxygen content, the distribution or amount of suspended solids, or disturbance patterns. Weir walls may interfere with groundwater flow, the movement of fauna or light availability. Ideally, weir controls would mimic the ambient tidal regime while simultaneously capturing potential artefacts. The specific design of weir controls can be tailored to address specific project goals. In this study, we found that water retention was similar between weir controls and controls, suggesting that it is possible to capture weir artefacts using weir controls without manipulating water retention.

The passive and active weir approaches represent a new and promising advancement in our ability to understand SLR impacts on wetland processes. When compared to mesocosm approaches, weirs are advantageous because they allow for larger-scale, *in situ* studies within natural or restored tidal wetlands; they do not require sod extraction; they minimize disturbance to the rhizosphere; and they can be maintained at relatively low cost and effort. Consequently, weirs may provide a more robust and realistic evaluation of SLR impacts on tidal wetlands and, when utilized along with other approaches, may generate unprecedented empirical data for predictive models of wetland persistence.

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Data accessibility

Water level data available from the Dryad Digital Repository: <http://dx.doi.org/10.5061/dryad.fv6fn>

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Weir installation.

Appendix S2. Diagram of water flow valves.

Appendix S3. Video of passive weirs.

Appendix S4. List of weir materials and approximate costs.