

1 Efficiency of Varying Sediment Traps under Experimental 2 Conditions Simulating Tidal Inundations

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10 LRH: Nolte, Butzeck, Baldwin, Felton, Jensen

11 RRH: Sediment trap efficiency

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ABSTRACT

13 Accelerated sea-level rise (SLR) is threatening tidal marshes worldwide. An important
14 control of tidal marsh survival under accelerated SLR is the sediment deposition.
15 Therefore, factors affecting sediment deposition rates (SDR) have been studied
16 extensively using various types of sediment traps. The efficiency of various sediment
17 traps has been compared in several studies, but most of these were conducted in
18 shallow lakes or rivers. In contrast, the efficiency of different sediment traps in tidal
19 marshes is unknown. Therefore, the aim of this study was to compare the trapping
20 efficiency of four frequently used sediment traps, namely flat traps constructed of either
21 tiles or floor mat, and circular traps with and without a lid, under controlled experimental
22 conditions simulating tidal inundations in a flume. The strong differences between
23 circular sediment traps (high efficiency) and both flat surface sediment trap methods
24 (low efficiency) found in this study were remarkable. Additionally, further evidence was
25 found for decreases of SDR with increasing distance to the inflow of the flume
26 (sediment source) and with decreasing suspended sediment concentration (SSC).
27 These findings indicate that trap design has a large influence on sedimentation rate
28 and that studies using different types of sediment traps are not directly comparable.

29

ADDITIONAL INDEX WORDS:

30 *Tidal marsh, wetland, sediment deposition, sedimentation.*

31

INTRODUCTION

32 Accelerated sea-level rise (SLR) has been recently discussed as a major threat to tidal
33 marshes (Craft *et al.*, 2009; Crosby *et al.*, 2016; Kirwan and Megonigal, 2013; Kirwan
34 *et al.*, 2016). An important control of tidal marsh survival under accelerated SLR is the
35 sediment deposition, which can be defined as the gravity-based deposition of organic

36 and inorganic particles during inundations (Allen, 2000; Nolte *et al.*, 2013; Temmerman
37 *et al.*, 2005). However, sediment deposition rates (SDR) in tidal marshes are highly
38 variable in space and time (Butzeck *et al.*, 2015; Reed, 1989). The spatial and temporal
39 variability is affected by various factors, including for example the distance to the
40 sediment source (Esselink *et al.*, 1998; Temmerman *et al.*, 2003) and the variability of
41 suspended-sediment concentration (Butzeck *et al.*, 2015; Fettweis, Sas and Monbaliu,
42 1998).

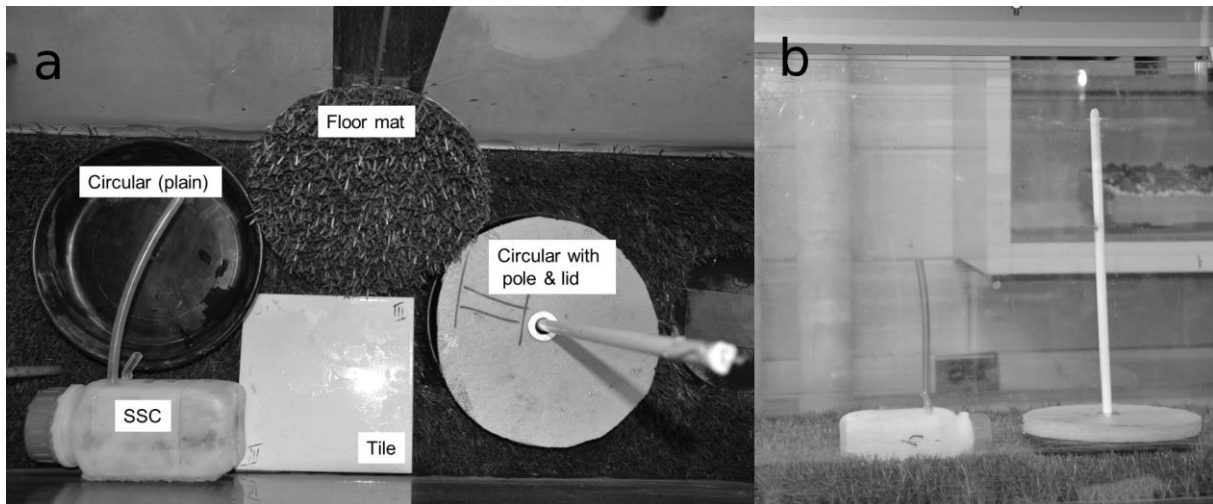
43 These factors affecting sediment deposition and surface elevation change have
44 been studied extensively (*e.g.*, Craft *et al.*, 2009; Kirwan and Megonigal, 2013;
45 Suchrow *et al.*, 2012) to understand and predict possible effects of accelerated SLR
46 on tidal marshes. However, these studies used a wide variety of methods such as
47 varying types of sediment traps to quantify SDR. The efficiency of different sediment
48 traps to measure SDR has previously been compared by several studies (see review
49 by Nolte *et al.*, 2013). Yet, most of these studies were conducted in shallow lakes or
50 rivers (Bloesch and Burns, 1980; Kozerski and Leuschner, 1999). Tidal marshes surely
51 differ from such shallow lakes and river systems in their hydrodynamics, which,
52 however, greatly affect sediment trap efficiency (de Swart and Zimmerman, 2009).
53 Therefore, the trapping efficiency of different commonly used trap designs needs to be
54 evaluated for intertidal systems. The most commonly used traps in tidal marshes are
55 either flat traps or cylindrical traps with a rim (Nolte *et al.*, 2013). Such a rim could affect
56 trapping efficiency as it prevents lateral relocation processes (Temmerman *et al.*,
57 2003), while a sediment trap with a flat surface might be vulnerable to washout of
58 sediment by heavy rain events (Steiger, Gurnell and Goodson, 2003). Among flat
59 sediment traps there are also different types such as, for example, flat ceramic tiles
60 (Pasternack and Brush, 1998) or AstroTurf® floor mats (Lambert and Walling, 1987).

61 The latter are used to mimic vegetation and a more natural surface roughness, which
62 might greatly affect trapping efficiency compared to, for example, ceramic tiles.
63 Additionally, it is unknown how a frequently used circular trap with a floatable lid
64 (Butzeck *et al.*, 2015; Temmerman *et al.*, 2003) compares to traps without such a lid.

65 To better understand the influence of trap design on sedimentation rate
66 measurements in tidal systems, the trapping efficiency of four frequently used
67 sediment traps were compared under controlled experimental conditions in a flume.
68 Results were additionally analyzed with respect to the distance to the sediment source,
69 and different suspended-sediment concentrations of the flooding water.

70 **METHODS**

71 Measurements were conducted at the Department of Environmental Science and
72 Technology, University of Maryland using a self-contained glass sided tilting re-
73 circulating flume. The flume consisted of a 7.3 m long, 0.3 m wide, and 0.45 m high
74 rectangular channel. The flat inner bottom of the flume was completely covered with a
75 soft and flexible artificial grass floor mat (stem length: 43 mm) to simulate the friction
76 of tidal marsh vegetation. Patches were cut out of the mat at the sampling points for
77 the sediment traps. Four different sediment traps were tested, including two different
78 flat traps, namely, ceramic tiles (*e.g.*, Pasternack and Brush, 1998) and circular
79 AstroTurf® floor mats (*e.g.*, Lambert and Walling, 1987), and circular traps with and
80 without a floatable lid (Butzeck *et al.*, 2015; Temmerman *et al.*, 2003; Figure 1, Table
81 1).



82

83 **Figure 1 (a)** Different types of sediment traps used to measure sediment-deposition rate and plastic bottles used
 84 to measure suspended sediment concentration (SSC). (b) Example of the setup in the flume for the test runs, which
 85 in this case include the SSC-bottle (left) and circular sediment trap with lid (right). The flume bottom was covered
 86 with an artificial floor mat which was removed at sampling locations

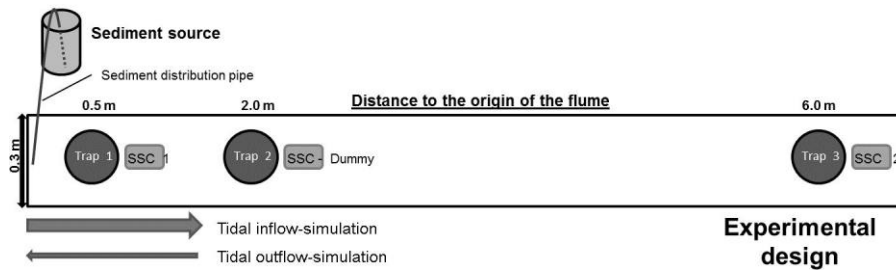
87 *Table 1 Area [cm²], size and specific features of the different sediment trap types.*

Trap type	Surface Area [cm ²]	size	specific feature
Circular trap (with lid)	280.55	18.9 cm (inside diameter)	3 cm high rim
Circular trap (plain)	280.55	18.9 cm (inside diameter)	3 cm high rim
Floor mat	314.16	20.0 cm (diameter)	at bottom level, stem length: 20 mm
Ceramic tile	232.26	15.24 x 15.24 cm	at bottom level

88

89 **Set-up and Test Procedure**

90 The sediment traps were installed at 0.5, 2.0 and 6.0 m distance from the inlet opening
 91 of the flume (Figure 2). The circular traps and floor mats were attached with Velcro®
 92 tape to the flume bottom. In addition the setup included bottles (adapted from Butzeck
 93 *et al.*, 2015; Temmerman *et al.*, 2003) to measure suspended-sediment concentration
 94 (SSC) positioned directly behind the sediment trap.



95

96 **Figure 2** Schematic drawing of flume to illustrate the experimental setup. The flume is indicated by the rectangular
 97 shape with the sediment source on the left side. The sediment source container is positioned adjacent to the flume
 98 but in an elevated position and is connected to the flume with a pipe. The tidal flow direction is indicated by arrows
 99 below the flume. The position of sediment traps with increasing distance to the origin of the flume is indicated using
 100 circles

101 The sediment used consisted of over 99 % of clay and fine silt and was collected from
 102 an oligohaline marsh at the Nanticoke estuary (Maryland, USA). Sediment was sieved
 103 with 1.18 mm and 425 μm sieves to remove large organic particles. A high (*SSC-high*:
 104 $\sim 100 \text{ mg l}^{-1}$) and a low sediment supply scenario (*SSC-low*: $\sim 65 \text{ mg l}^{-1}$) were applied
 105 by mixing the sediment with a defined quantity of water in a container positioned
 106 adjacent to the flume but in an elevated position. To prevent the sediment from settling
 107 inside the container, an air pump was installed in the container to provide a constant
 108 movement of the sediment-water mixture. The sediment-water mixture was then
 109 transported from the container to the inlet opening of the flume via a pipe using low
 110 pressure at the flume end of the pipe and gravity. The outlet of the flume was closed
 111 during the entire experiment to simulate inundation heights of 15 cm above surface.
 112 Inundation heights were measured at Trap 1. The duration of the tidal water inflow was
 113 between 8 and 11 minutes. Water samples ($\text{SSC}_{\text{Initial}}$) were taken automatically as
 114 soon as the inundating water submerged the inlet opening of the SSC bottle. After
 115 reaching the maximum inundation height of 15 cm the inflow of the water and the
 116 discharge of the sediment water-mixture were stopped. At maximum inundation SSC-
 117 bottles were replaced to obtain SSC-samples ($\text{SSC}_{\text{Slack}}$) from the outflowing water. The
 118 outflow of the water (ebb) occurred over the inlet opening of the flume. Total inundation
 119 time of one run of the tidal simulation lasted between $37 \pm 2 \text{ min}$ (short inundation runs)

120 and 61 ± 2 min (long inundation runs). Long inundation runs with *SSC-low*, and short
121 inundation with *SSC-high* were performed, using one trap type per run. Ten runs with
122 each of the four trap types of the *SSC-low* and the *SSC-high* simulations were
123 conducted in random order.

124 After each run, the sediment was rinsed from the sediment trap with distilled water into
125 aluminum boxes and dried at 105 °C to a constant weight. Values were then converted
126 into sediment deposition rates [g m^{-2}] per tidal inundation. SSC-samples were well
127 mixed before taking a subsample of 200 ml, which was vacuum-filtrated through pre-
128 weighed 0.45 μm glass fiber filters (Whatman™). Afterward, SSC-samples were dried
129 at 60 °C for 4 h to constant weight to determine SSC [mg l^{-1}].

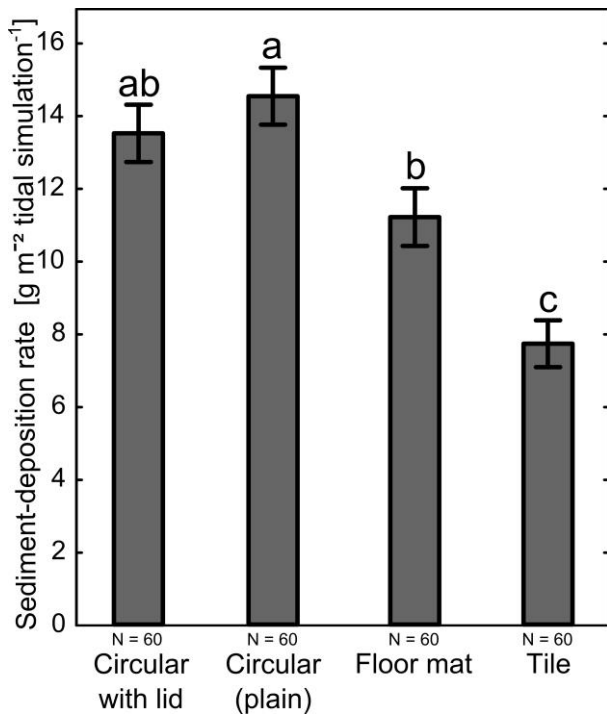
130 **Statistical Analysis**

131 Data met the assumptions of normality and homogeneity of variance. Thus a three-
132 factorial ANOVA was used to analyze differences in SDR between sediment trap types.
133 Sediment trap type, distance to the inlet of the flume, and sediment supply (*SSC-low*/
134 *SSC-high*) were included as factors. If a significant effect was detected, pairwise
135 comparisons using Bonferroni post-hoc tests were applied. All statistical analyses were
136 done with STATISTICA 10 (StatSoft Inc. 2010).

137 **RESULTS**

138 Mean sediment deposition rate significantly differed between sediment trap types
139 (Figure 3, Table 2). The highest SDR was found in plain circular traps. According to
140 the post-hoc tests SDR in circular traps with a floatable lid were slightly, but not
141 significantly lower (7 %) than SDR in plain circular traps without a floatable lid.
142 Sediment traps made of floor mats differed significantly from both tiles and plain
143 circular traps, but the post-hoc test indicates no significant difference between floor

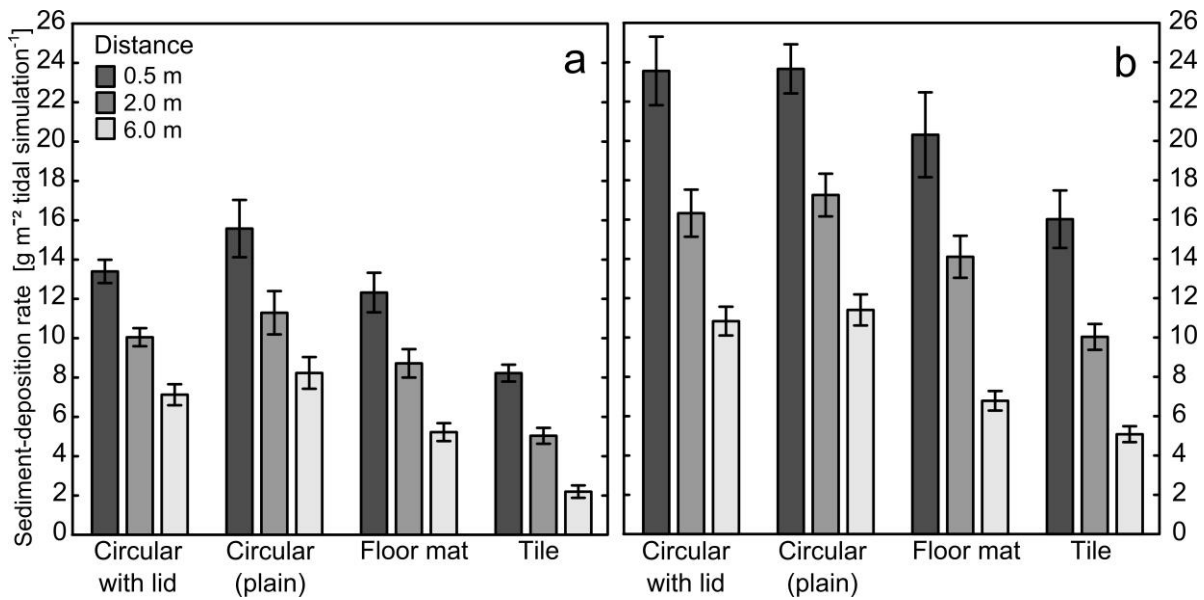
144 mats and circular traps with a lid (Figure 3). The lowest SDR were found on tiles, which
 145 significantly differed from all other sediment trap types. In total, the SDR of tiles was
 146 31 % lower than the SDR of floor mats, and 43 to 47 % lower than the SDR of circular
 147 traps with lid and plain circular traps, respectively.



148
 149 **Figure 3** Plotted values are means (\pm SE) of sediment-deposition rates [g m⁻²] of four different sediment traps.
 150 Letters denote statistical differences between sediment-trap types ($p < 0.05$) based on post-hoc tests

151
 152 Results revealed strong effects of distance to the inlet of the flume (Figure 4,
 153 Table 2), and sediment supply (Figure 4, Table 2) on SDR. All sediment trap types
 154 showed a highly significant decrease in SDR with increasing distance from the inlet of
 155 the flume (Figure 4, Table 2), although the reduction was greater under high than under
 156 low sediment supply rates (significant distance \times sediment supply rate, Table 2). A
 157 higher SSC (Figure 4) resulted in a higher SDR, but the effect of SSC varied with
 158 distance (Table 2, significant distance \times sediment supply rate). With higher sediment
 159 supply, the percent decreases of SDR with distance were slightly higher. The
 160 interaction effects trap type \times ssc and trap type \times distance were not significant (Table

161 2) indicating the differences in trapping efficiency of different sediment traps to be
 162 constant regardless of the spatial and temporal variation represented by distance to
 163 the inlet and SSC, respectively.



164

165 **Figure 4** Plotted values are means (\pm SE) of sediment-deposition rates [g m^{-2}] of different sediment traps, depending
 166 on distance to the origin of the flume, during (a) low and (b) high suspended sediment concentration (SSC)

167

168 *Table 2 Results of the three-factorial ANOVA for effects of trap types, distance to the origin of the flume and SSC*
 169 *on sediment-deposition rate.*

Factor	Sediment-deposition rate	
	<i>F</i>	<i>p</i>
Trap type	61.5	***
Distance	212.7	***
Sediment supply	273.3	***
Trap type \times Distance	0.4	<i>n.s.</i>
Distance \times Sediment supply	13.0	***
Trap type \times Sediment supply	1.3	<i>n.s.</i>
Trap type \times Distance \times Sediment supply	0.2	<i>n.s.</i>

n.s. not significant, *** $p < 0.001$

170

171

DISCUSSION

172 In line with the expectations, trapping efficiency was found to differ significantly
 173 between commonly used sediment trap designs. These differences in trapping

174 efficiency were constant regardless of the conditions (distance to inlet and SSC). The
175 strong differences between circular sediment traps (high efficiency) and both flat
176 surface sediment traps methods (low efficiency) found in this study were remarkable.
177 Therefore, studies using different types of sediment trap may not be directly
178 comparable due to differences of the trapping efficiency of the various available trap
179 designs (Nolte *et al.*, 2013).

180 During this study, SDR in both circular sediment trap types was higher than in
181 flat sediment trap types. This difference between the circular sediment trap (with a rim)
182 and the flat surface sediment trap might indicate re-suspension and/or lateral
183 sediment-transport processes. This might occur on different scales depending on
184 sediment trap type. Some studies have found that collected sediment trapped by flat
185 surface traps is sensitive to washing off by rain and partly by tides (Gardner, 1980;
186 Kozerski and Leuschner, 1999). Although it can be expected that the rim of the circular
187 sediment trap prevents trapped sediment from lateral dispersal to the surrounding
188 surface (Neubauer *et al.*, 2002), it might also prevent a relocation of sediment from the
189 surrounding surface into this sediment trap type. No or only a marginal amount of
190 re-suspension of fresh deposited sediment from circular sediment traps was found by
191 both Reed *et al.* (1999) and Temmerman *et al.* (2003). The higher SDR in circular traps
192 compared to flat tiles found here might also be due to reduced bottom shear stress
193 (Kozerski and Leuschner, 1999), while simultaneously the rim of the circular trap
194 induced local flow acceleration and the formation of eddies which can increase
195 deposition rates (Butman, Grant and Stolzenbach, 1986).

196 When comparing two types of flat sediment traps higher SDR was found on floor
197 mats compared to ceramic tiles, probably because of the higher surface roughness of
198 the floor mat. This is in line with Steiger, Gurnell and Goodson (2003), who suggested

199 the usage of floor mat sediment traps for riparian sedimentation studies as the surface
200 simulates surrounding vegetation. However, it could be argued that the commonly
201 available floor mats do not represent the vegetation sufficiently, as vegetation in many
202 marshes is taller than the stem length of the floor mat (Leonard and Luther, 1995;
203 Neumeier and Amos, 2006; Rupprecht *et al.*, 2015). One exception might be marshes
204 where canopy height is reduced due to livestock grazing *e.g.* in the Wadden Sea region
205 (Nolte *et al.*, 2014) or in the Yangtze estuary (Yang, Nolte and Wu, 2017).
206 Nevertheless, Steiger, Gurnell and Goodson (2003) argue, that the increased surface
207 roughness of the floor mat provides an easy handling during collecting and processing.
208 Also Kleiss (1996) used flat surface sediment traps with a rough upper surface to
209 minimize re-suspension of deposited sediments. Contrastingly, Mansikkaniemi (1985)
210 found no significant differences between flat sediment traps with and without attached
211 floor mats during a shallow water study, possibly because of different hydrodynamic
212 forcing. Also Steiger, Gurnell and Goodson (2003) did not find significant differences
213 between flat surface sediment traps with varying roughness.

214 No significant difference between circular sediment traps with and without a lid
215 was found in this experimental flume study. In field studies the floatable lid is supposed
216 to protect trapped sediment from splashing out by heavy rain events during low tides
217 (Temmerman *et al.*, 2003), which of course did not occur in the flume. In their study
218 Bloesch and Burns (1980) stated that the geometry of circular sediment traps (ratio of
219 height to diameter) also affects the amount of re-suspension. However, in this case the
220 circular sediment traps were identical except for the lid. The slightly higher SDR found
221 in circular sediment traps without a lid might be partly explained by sediment adhered
222 below the lid or on the pole.

223 Significant decreases of SDR with increasing distance to the inflow of the flume
224 (sediment source) and decreasing SSC were found for all sediment trap types. SDR
225 has previously been found to relate to distance to the sediment source, like marsh
226 edge and nearest creek (e.g., Esselink *et al.*, 1998; Butzeck *et al.*, 2015; Temmerman
227 *et al.*, 2003), as well as to seasonal and spatial variability of SSC (e.g., Butzeck *et al.*,
228 2015; Fettweis, Sas and Monbaliu, 1998; Temmerman *et al.*, 2003).

229 CONCLUSIONS

230 Based on the clear difference between the flat and circular trap types found in this
231 study, the use of flat traps would be recommended to prevent overestimation of SDR.
232 However, in systems with very high SDR, the flat tiles might be less p as sediment
233 might be lost during the collection process. Therefore, the choice of sediment trap
234 design should be made taking various aspects of the study site and study design into
235 account (see review by Nolte *et al.*, 2013). It is furthermore concluded, that differences
236 in trapping efficiency impede the comparability of sediment trap types commonly used
237 in tidal wetland studies. This especially needs to be considered in meta-analysis of
238 studies assessing marsh-resilience to sea-level rise (e.g., Crosby *et al.*, 2016; Kirwan
239 *et al.*, 2016). Standardization of sediment traps for intertidal habitats would be
240 necessary for a direct comparison. As a next step, field studies to compare different
241 sediment trap types under different inundation regimes, flow velocities, as well as
242 different marsh types (mineral and organic) would be recommended. Short-term
243 measurements of SDR with sediment traps like those compared in this study are
244 especially useful for analyzing spatio-temporal variation in SDR and in their predictors.

245

ACKNOWLEDGEMENTS

246 This study was funded by the Federal Ministry for Education and Research within the
247 research project KLIMZUG-NORD and supported by the Estuary and Wetland
248 Research Graduate School Hamburg (ESTRADE) as member of the State Excellence
249 Initiative (LEI) funded by the Hamburg Science and Research Foundation. We would
250 like to thank Jenny Allen, Metthea Yepsen, Leah Beckett, Ryan Adams and Brandon
251 Winfrey for their assistance with field work and laboratory work.

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