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Recovery of salt marsh vegetation after ice-rafting

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ABSTRACT: Sediment transport on salt marsh platforms is usually brought about through storm events and high tides. At high latitudes, ice-rafting is a secondary mechanism for sediment transport, redistributing sediment from tidal flats, channels, and ponds to marshland. In January 2018, winter storm Grayson hit the North Atlantic coast, producing a large storm surge and a significant decrease in temperature. The Great Marsh in Plum Island Sound, Massachusetts, USA, experienced an unprecedented sediment deposition due to ice-rafting, burying marsh vegetation. Plant vegetation recovery was investigated in 17 sediment patches, dominated by *Spartina patens*, *Distichlis spicata*, *Juncus gerardi*, and *S. alterniflora*. The analysis was carried out considering the number of stems and stem height for each vegetation species. *D. spicata* firstly occupied bare patches, while *S. patens*, once smothered by sediment, regrew slowly. The number of stems of *S. patens* inside the sediment patches recovered, on average, after 2 growing seasons. The number of *J. gerardi* stems was not significantly affected by ice-rafted sediment deposition. *S. alterniflora* dynamics were different depending on physical and edaphic conditions. At some locations, *S. alterniflora* did not recover after sediment deposition. The deposition of the sediment layer had a positive effect on vegetation vigor, increasing stem height and maintaining high stem density. The results suggest a beneficial effect of sediment deposition not only for marsh accretion, but also for marsh vegetation growth, both of which are fundamental for marsh restoration.

KEY WORDS: Salt marsh · Salt marsh vegetation · Sediment deposition · Vegetation recovery · Ice-rafting

1. INTRODUCTION

Salt marshes have long been recognized for their role in coastal protection (Gedan et al. 2009, 2011, Shepard et al. 2011), maintenance of habitats and ecosystems (Boorman 2003), carbon storage (Mcleod et al. 2011, Kirwan & Mudd 2012, Ouyang & Lee 2014), nutrient cycling (Sousa et al. 2010), fishery support (Boesch & Turner 1984, Rozas et al. 2005), water quality improvement (Ewel 1997), and many other services (Boorman 2003). Salt marshes are dynamic systems that respond quickly to both hydrological and biological drivers. They thrive when accretion rates driven by sediment transport balance sea level rise. Tidal flooding supplies marshes with sediments (Stumpf 1983, Christiansen et al. 2000), and marsh vegetation helps to trap this material (Stevenson et al. 1988, Boorman et al. 1998). If sea-level rise accelerates, sediment accumulation cannot keep pace with accommodation space and marsh existence is undermined (Stevenson et al. 1986, Kirwan & Temmerman 2009). Long-term stressors, such as climate change or anthropogenic pressure, and episodic disturbances, such as storm events, can lead to salt marsh loss and alter the original vegetation species composition (Ellison et al. 2005, Mcleod et al. 2011). During storm events, significant amounts of sediment are transported and deposited on the marsh surface. This material builds elevation, supplies nutrients, and stimulates plant growth (McKee & Cherry 2009, Baustian & Mendelssohn 2015, FitzGerald et al. 2020). Healthy vegetation promotes belowground organic accumulation and marsh resilience (FitzGerald et al. 2020). Although hurricanes

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can destroy or damage coastal wetlands, sediment deposition due to these extreme events has been well documented (McKee & Cherry 2009, Baustian & Mendelssohn 2015). Hurricane Katrina changed the elevation of Mississippi brackish marshes, by adding 3 to 8 cm of sediment to the soil surface, thus counteracting subsidence (McKee & Cherry 2009). A study conducted in the same Louisiana coastal area not only confirmed the positive effect of sediment deposition due to hurricanes, but also suggested the beneficial effects of sedimentation for primary production (Baustian & Mendelssohn 2015).

Ice-rafting is a secondary mechanism for sediment deposition that redistributes sediments from tidal flats, channel beds, and ponds to the inland vegetated marsh surface (Argow et al. 2011). This phenomenon occurs in northern temperate regions and is strictly dependent on temperature, precipitation, storm surges, and intertidal morphology (Barnes et al. 1982). During winter, when temperatures are particularly low, water freezes at low tide on mudflats, ponds, and tidal channels. A subsequent high tide or storm surge can detach ice sheets from bottomset beds, entraining and transporting thick layers of compacted sediment on the adjacent marsh surface. When the water level lowers, these ice blocks deposit on the vegetated soil and subsequently melt once temperature increases (Argow & Fitzgerald 2006, Argow et al. 2011). Once deposited, ice-rafted sediment layers are hard to remobilize. In January 2018, winter storm Grayson hit the North Atlantic Coast, causing ice-raft deposition at an unprecedented scale in the Great Marsh of Massachusetts, USA (FitzGerald et al. 2020). The consequences of this extreme event on marsh vegetation and invertebrate communities were documented in different studies (Moore et al. 2021, Wittyngham et al. 2022). Aerial images and field surveys were used to estimate sediment thickness, ranging from 1 to 90 mm, and vegetative response to ice-rafting (Moore et al. 2021). The number of stems and vegetation biomass were used to estimate plant regrowth after Grayson (Wittyngham et al. 2022). Vegetation regrowth in a disturbed area can be related to edaphic and biotic factors. In favorable soil conditions, it is likely that more species can survive (Bertness & Ellison 1987, Bertness 1991, Pennings & Callaway 1992). Inter-specific competition is also important to determine natural patterns of zonation (Ellison 1987).

In this research, we studied *Spartina patens*, *Distichlis spicata*, *Juncus gerardi*, and *S. alterniflora* regrowth after sediment deposition due to ice-rafting and their consequent inter-specific competition. (The updated taxonomy of *S. alterniflora* and *S. patens* is respectively *Sporobolus alterniflorus* and *Sporobolus pumilus*, but we chose to use the older name for consistency with previous published work.) *S. patens* dominates the high marsh in Massachusetts and is unable to persist in the frequently flooded low marsh area (Bertness 1991). *J. gerardi* is mostly present along the terrestrial border. *D. spicata* is a perennial species that can be found in high marsh habitats at low densities mixed with the dominant species and at higher densities in discrete patches (Bertness 1991). This species is more resistant to wrack burial but is subordinate to *S. patens*. According to Bertness (1991), *D. spicata* vegetatively expands on long adventitious rhizomes, and it is the first to invade bare patches. In time, it is replaced by *S. patens*, characterized by denser turf, and *Juncus gerardi* in the marsh areas where these species are dominant (typically after 2–4 yr). Cordgrass *S. alterniflora* dominates the low marsh habitats because it is able to oxygenate its rhizosphere in anoxic soils (Bertness 1991). In the absence of neighboring competitors, *S. alterniflora* can vigorously grow in low and high marsh. Competitive displacement restricts this species mostly to the low marsh. New England marshes are primarily occupied by *S. alterniflora* in short and tall form based on their location (Shea et al. 1975). Tall *S. alterniflora*, reaching heights of 1.25–2 m, is commonly found in the intertidal zone of the low marsh, while the short form, reaching heights less than 0.5 m, can be found in patches in the high marsh (Shea et al. 1975). Differences in height are correlated to environmental parameters such as nitrogen and oxygen availability and soil aeration (Ellison et al. 1986). In this study, we focused on 2 parameters to describe vegetation recovery: number of stems per square meter for each species and stem height. We estimated how much time each species needed to recover after the Grayson ice-rafting event, and whether sediment deposition could help vegetation regrowth. Wittyngham et al. (2022) conducted a similar study concentrating on plant and invertebrate community regrowth over 18 mo after the same event. Our study was longer in duration and concentrated on plant communities.

2. MATERIALS AND METHODS

2.1. Study site

The Great Marsh is the largest salt marsh in New England, covering a 40 km^2 area (Moore et al. 2021)

(Fig. 1a). The marsh experiences semidiurnal tides with a mean tidal range of 2.6 m and a tidal prism of around 32 × 10^6 m^3 (Vallino & Hopkinson 1998, Farron et al. 2020). Farron et al. (2020) defined 4 zones based on the relative elevation with respect to mean sea level (MSL): open water (<0.18 m), low marsh (0.18–1.18 m), high marsh (1.18–1.98 m), and upland (>1.98 m). According to salt marsh elevation and the frequency of tidal inundation, different vegetation species can be found.

On 4 January 2018, winter storm Grayson triggered an unprecedented sediment deposition event in the Great Marsh. Water levels measured at the Boston NOAA station 8447930 reached 3 m above MSL, with a storm surge of 2 m. A sediment volume equivalent to 12–15 yr of marsh accretion was

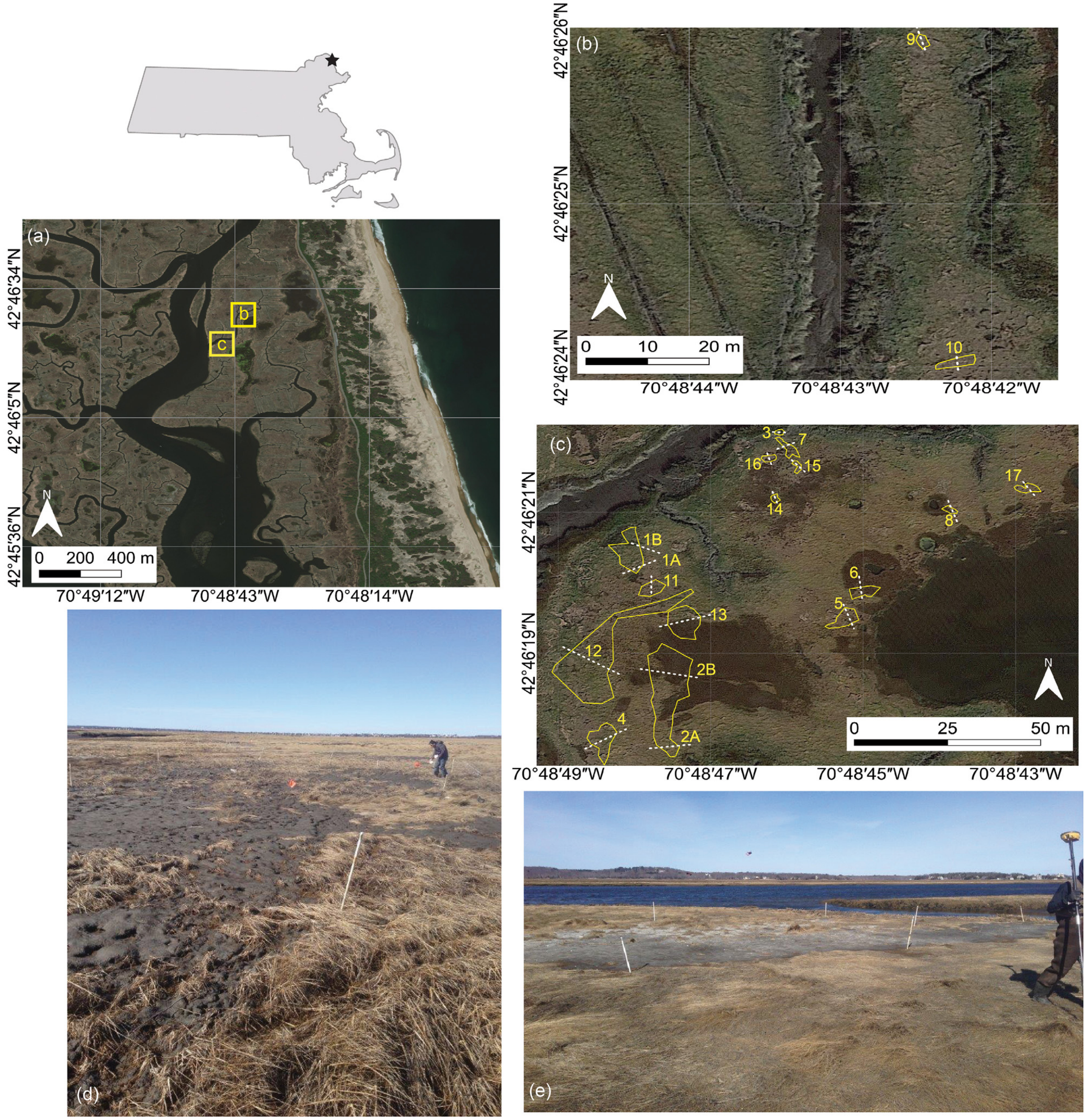

Fig. 1. (a) Study site in the Great Marsh, Massachusetts, USA. (b,c) Sediment patches detected after the storm event of January 2018. The established transects are also indicated. (d,e) Photos of mud patches taken in February 2018, after storm Grayson occurred

deposited at some locations in the Great Marsh via ice rafts (Stopak et al. 2022, Wittyngham et al. 2022). Due to the high marsh platform elevation, the inundation frequency in this area is low (twice per month during spring tides when water depth above the marsh platform is a few centimeters or even lower at the highest elevations according to NOAA station 8447930). Because of this, the ice sheet transporting sediment layers is deposited and melts at the same location, not being subjected to refloating.

2.2. Methods

In the Great Marsh, 17 sediment patches deposited by ice rafts were identified in February 2018 (Fig. 1). Latitude, longitude, and elevation data of each patch were collected (Table 1) using a TOPCON Real-Time Kinematic GPS system. Spatial coordinates referred to the midpoint of each patch, while the elevation inside and outside the patch was calculated as the average plot elevation inside and outside along the transect. Patch area was calculated in QGIS using coordinates of patch boundary. For each patch, sediment thickness along the transect was measured from sediment samples using a caliper (Table 1). Sediment samples were analyzed using wet sieving (Robertson et al. 1984) to separate sand and silt/clay fractions. Approximately 50 cm^3 of each sediment sample were first sonicated for 15 min at room temperature (~24°C) in a beaker, filled with 100 cm^3 of water, to separate aggregated particles. Fine sediment was then separated from coarse sediment using sieves of 10, 63, and 230 µm. Coarser material retained in the 10 µm sieve is classified as 'debris and vegetation'. Sediments were dried at a temperature of 60°C. Finally, once weighed, the percentage of fine and coarse material was calculated. In addition, undisturbed samples were collected to calculate the percentage of organic matter (OM). They were dried as the previous ones, ground, and put in a furnace at 375°C (loss on ignition). Table 2 details the composition of the sediment samples. Six patches were dominated by *Spartina patens* and *Distichlis spicata*; 2 exclusively by *S. patens*; 5 by *S. patens*, *Distichlis spicata*, and *Juncus gerardi*; and 4 by *S. alterniflora*.

In each patch, vegetation data were collected along a transect, within square plots. Three stations were established inside the sediment patch and 3 outside in the undisturbed area as reference stations. A 25 cm quadrat was placed at the exact same location every year, using a permanent PVC pole for reference, with the top-most point of the quadrat ori-

Table 1. Characteristics of 17 sediment patches deposited by ice rafts in the Great Marsh, Massachusetts, USA, identified in February 2018 following winter storm Grayson. Patch thickness is expressed as an average value along with its variance

Patch	Transect no.	Mean latitude (° N)	Mean longitude (° W)	Mean elevation on NAVD88 (m) outside patch	Mean elevation on NAVD88 (m) inside patch	Distance from channel (m)	Patch area (m^2)	Patch thickness along transect (cm)
1	1A	42.7723	70.8132	1.37	1.39	12.76	86.46	2.3 ± 0.78
	1B	42.7724	70.8132	1.41	1.38	19.84		3.0 ± 0.61
2	2A	42.7718	70.8131	1.35	1.36	32.48	307.81	3.2 ± 1.70
	2B	42.7718	70.8132	1.33	1.36	36.69		3.6
3	3	42.7728	70.8128	1.16	1.21	5.04	4.20	3.0
4	4	42.7717	70.8134	1.40	1.40	13.11	63.84	3.1 ± 0.57
5	5	42.7721	70.8126	1.46	–	66.27[a]	36.75	2.8
6	6	42.7720	70.8125	1.43	1.47	69.43[a]	26.71	1.8
7	7	42.7727	70.8127	1.37	1.38	9.97	17.94	1.9
8	8	42.7725	70.8122	1.46	1.46	31.01	7.14	2.8 ± 0.68
9	9	42.7740	70.8117	1.34	1.37	10.97	5.38	2.7
10	10	42.7732	70.8117	1.40	1.43	19.34	13.75	4.1 ± 0.60
11	11	42.7722	70.8132	1.34	1.38	29.93	29.44	3.9 ± 2.23
12	12	42.7722	70.8131	1.38	1.39	25.22	408.09	2.7
13	13	42.7721	70.8131	1.37	1.37	46.72	87.97	–
14	14	42.7725	70.8128	1.36	1.39	28.97	5.47	–
15	15	42.7727	70.8127	1.38	1.40	19.83	6.58	2.0
16	16	42.7727	70.8128	1.40	1.41	14.09	8.43	2.3 ± 0.78
17	17	42.7726	70.8119	1.48	1.50	32.65[a]	16.38	3.0 ± 0.61

[a] Patch was close to a pond

Table 2. Sediment analysis results for each sediment patch deposited by ice rafts in the Great Marsh, Massachusetts, USA. Sediment samples were collected in February 2018. OM: organic matter or portion of soil that is composed of living and dead things in various states of decomposition. NA: data not available

Patch	% silt and clay	% sand	% debris and vegetation	%OM
1	85.25	14.47	0.28	8.21
2	89.89	7.77	2.34	14.05
3	73.23	21.60	5.17	11.16
4	76.40	23.54	0.06	7.01
5	56.71	41.62	1.67	7.89
6	88.19	11.43	0.38	9.09
7	82.67	17.29	0.04	9.29
8	76.51	22.48	1.00	10.14
9	80.48	19.04	0.48	10.71
10	85.03	14.29	0.68	9.73
11	91.19	8.77	0.04	18.61
12	89.20	10.43	0.37	10.26
13	94.78	4.65	0.56	16.95
14	NA	NA	NA	NA
15	88.26	7.61	4.13	17.10
16	68.58	31.31	0.11	7.79
17	77.51	21.61	0.88	10.93

ented north with a compass. The vegetation stems of each species inside each plot were counted. The growing season of these species is between late spring and summer. The height of 20 randomly chosen stems was measured in each plot for each species. The vegetation survey was carried out in September 2018, September 2019, September 2020, October 2021, and September 2022 at the end of the growing season. Mean number of stems for each species was determined both outside and inside plots. A 2-way ANOVA with interaction followed by a post hoc Tukey test was performed to evaluate significant differences between the average number and height of stems inside and outside sediment patches over time. The significance level was set to 90% to guarantee a good balance between sample size and statistical power. For some patches, due to the small size of the data set, the statistical results can be misleading (Cohen 2013). In 2021 and 2022, the presence of dead biomass (wrack) in each plot was recorded. Wrack usually consists of *S. alterniflora*. Plants in New England marshes grow from May to September, and in the late fall they reallocate all of their resources belowground. The dead aboveground leaves and stems are easily transported by tides. Wrack disturbance kills vegetation stems depending on the wrack thickness and burial duration (Pennings & Bertness 2001).

Two soil moisture sensors (TEROS, by METER) were installed inside and outside of patch 10 (see Fig. 1), which was dominated by *S. patens* and *D. spicata*. This patch was selected because it was sufficiently far away from channels and ponds. Therefore, we assumed that eventual data differences in edaphic conditions could be attributed to the presence of the mud layer rather than to groundwater dynamics. The instruments were placed 13 cm below the ground surface, at the same distance of around 20 m from the main channel, and collected data of soil specific conductivity (at 25°C), a measure of soil salinity, water content, and temperature every 30 min from September 2019 to November 2019, after the number of stems had begun to recover. These data were used to correlate long-term ecological patterns to soil properties. An unpaired *t*-test with a significance level of 5% was used to statistically compare water content, temperature, and electrical conductivity outside and inside the patches.

All statistical analyses were done using R–4.2.2 for Windows and R-studio 2022.12.0+353. The libraries 'stats', 'lmeans', and 'multcomp' were used to perform *t*-tests, ANOVAs, and post hoc Tukey tests.

3. RESULTS

3.1. Stem number

An overall analysis of *Spartina patens*, *Distichlis spicata, Juncus gerardi*, and *S. alterniflora* stems inside and outside the patches is presented in Fig. 2. In February 2018, right after the storm event, patches were bare and consisted of 80–90% clay (Table 2). In September 2018, we could identify the first vegetation stems. Vegetation recovery is reached when the number of stems in the plots inside the patches is not significantly different from the number of stems outside of the plots, considered as reference values. Two-way ANOVA results suggest a significant difference of *S. patens* stems over time and according to position ($p < 0.1$) (Table 3). In particular, stems inside the patches were 70% significantly less dense than outside after the first growing season ($p < 0.1$). In 2019, the number of stems inside the patches recovered ($p > 0.1$), reaching values 20% lower than outside. After 2 growing seasons, growth was regulated by other disturbances (e.g. wrack) and interspecies competition. After the storm surge event, in September 2018, *D. spicata* rapidly colonized the bare patches (Fig. 2b). The total number of *D. spicata* stems did not significantly differ between

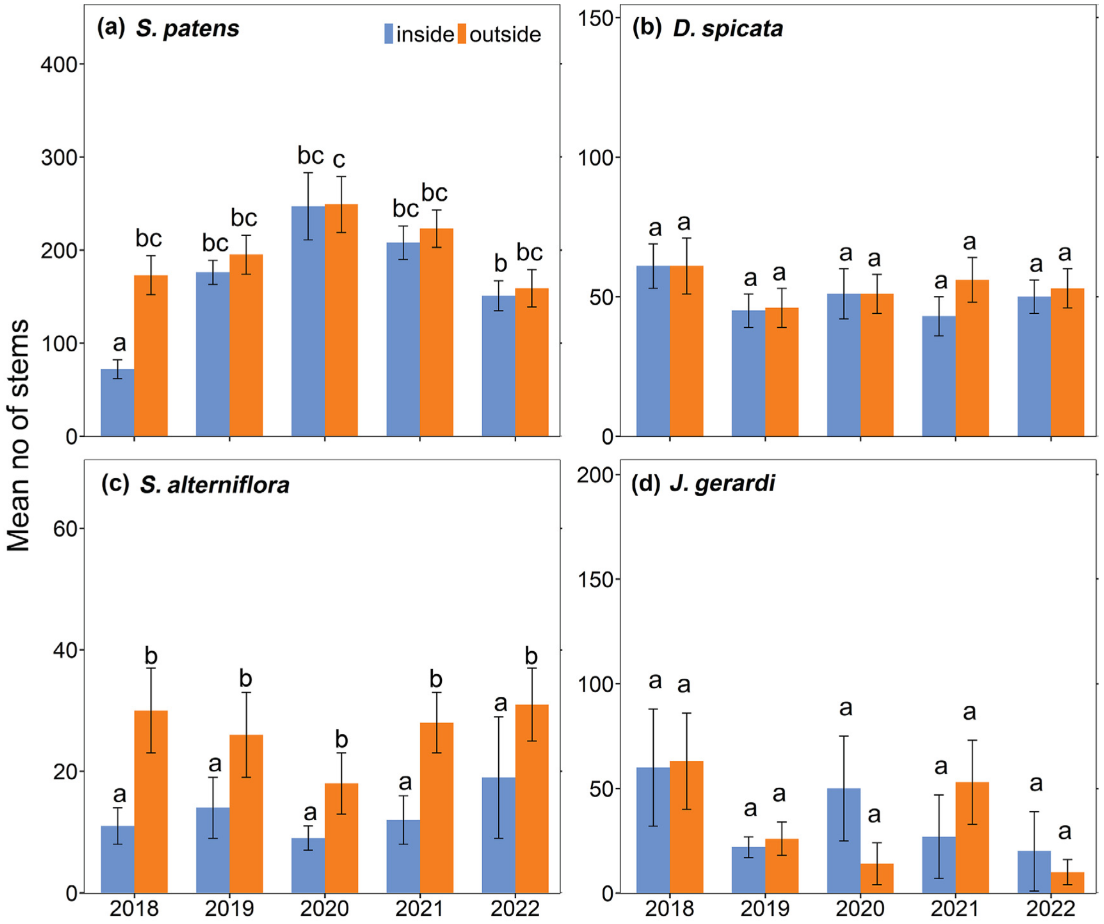

Fig. 2. Total number of (a) *Spartina patens*, (b) *Distichlis spicata*, (c) *Spartina alterniflora*, and (d) *Juncus gerardi* stems inside and outside of sediment patches deposited by ice rafts in the study area over time. Error bars: SE. Letters over bars: post hoc Tukey test results (α = 0.1)

inside and outside the patches over time (Fig. 2b, Table 3) ($p > 0.1$), although we detected a slightly higher density inside the patches. Two-way ANOVA results showed a significant difference in *S. alterniflora* stem density outside and inside the patches (Table 3, Fig.2c) ($p < 0.1$). Due to the smaller size of the data set, the difference between inside and outside each patch after the first growing season was not statistically significant; however, stems inside were 60% less dense than outside. The number of stems inside the patches remained quite constant and lower than outside over the next several years (Fig. 2c). The number of stems of *J. gerardi* did not differ in position or over time (Fig. 2d, Table 3) ($p > 0.1$).

The mean number of stems for each transect from September 2018 to October 2022 is shown in Figs. S1–S6 in the Supplement at www.int-res.com/articles/suppl/m710p057_supp.pdf. Tables S1–S4 summarize the 2-way ANOVA results for each transect. The analysis confirms the results obtained in the overall study for *S. patens* and *D. spicata*. The post hoc test results, reported in the bar plots, are influenced by high size effect (3 data for each level of treatment) and consequently could provide a misleading interpretation. Independently from them, we can see that the number of stems of *S. patens* inside the patches reached the number outside after 2 growing seasons in the transects, outcompeting *D. spicata* (Figs. S1, S2, & S6; Tables S1 & S2). After recovery, in transects 1A, 4, 7, 8, 12, and 17, the number of *S. patens* stems inside reached values slightly higher than outside, suggesting a beneficial effect of sediment deposition on *S. patens* growth. This effect can also be detected for *D. spicata* in the overall analysis and was confirmed by looking at a single patch (Fig. 2b; Figs. S1 & S6). Sediment deposition had a different effect in patches dominated by *S. alterniflora* (Figs. S3–S5, Table S3). In transect 6 (Fig. S3), the number of stems of short-form *S. alterniflora* was similar over the

Table 3. Summary results of 2-way ANOVA model for total number of stems of each species outside and inside of sediment patches deposited by ice rafts: stems~position+year+position:year. Position and year are main effects, and position:year represents the interaction. **Bold** text is used to identify significant differences in the levels of each effect. Significance level set at 10% ($\alpha_{crit} = 0.1$). *F*- and p-values are the results of the statistical test and need to be compared to F_{crit} and α_{crit}

Effect Test	df	Mean of squares	Position *F*	F_{crit}	p
Species					
Spartina patens	1	218870	**10.02**	2.72	**1.60×10^{-3}**
Distichlis spicata	1	840.74	0.35	0.35	0.57
S. alterniflora	1	5454	**13.11**	2.75	**4.50×10^{-4}**
Juncus gerardi	1	1.14	4.00×10^{-4}	2.74	0.98
Effect Test	**df**	**Mean of squares**	**Year *F***	**F_{crit}**	**p**
Species					
S. patens	4	238581	**10.92**	1.96	**1.69×10^{-8}**
D. spicata	4	1704.26	0.70	1.96	0.59
S. alterniflora	4	432.90	1.04	1.99	0.39
J. gerardi	4	3017.84	1.15	1.99	0.34
Effect Test	**df**	**Mean of squares**	**Position:Year *F***	**F_{crit}**	**p**
Species					
S. patens	4	38863	1.78	1.96	0.132
D. spicata	4	751.68	0.31	1.96	0.87
S. alterniflora	4	80.20	0.19	1.99	0.94
J. gerardi	4	1544.88	0.59	1.99	0.67

years and between outside and inside the patch. In transect 3 (Fig. S4), the number of stems of tall-form *S. alterniflora* inside the patch was 55% lower than outside after the first growing season and tended to slightly decrease over time (Fig. S4b). As a consequence of sediment deposition and increasing elevation (Table 1), *S. patens* invaded the bare patch, with the number of stems quite constant over the following years (Fig. S4a). In transect 2B, after the storm, the number of short-form *S. alterniflora* stems drastically decreased (80% lower) and never recovered (Fig. S5c). *D. spicata* occupied bare patches after the first growing season (Fig. S5b), but *S. patens* density kept increasing, outcompeting the fugitive species (Fig. S5a). In transect 14, *S. alterniflora* was not affected by sediment deposition, and the number of stems remained constant over time.

The presence of wrack, detected in October 2021 and September 2022, influenced the average values of those years in many plots (Figs. S1a,b, S2b, & S6a–c,o,p,q), reducing the number of stems. By considering only plots where wrack was not present, we can estimate the average number of stems in undisturbed conditions. This estimate is qualitative and not statistically useful because only few plots were used. Wrack can lower the number of *S. patens* stems by between 10 and 60% compared to the undisturbed plots (dotted line in Figs. S1a, S2b, & S6a–o,), inhibiting growth by reducing light levels and providing a physical barrier to plant emergence. The number of stems of *D. spicata, J. gerardi*, and *S. alterniflora* was less sensitive to wrack deposition (Figs. S1b, S3, & S6b,c,p,q).

3.2. Stem height

Results of 2-way ANOVA suggest that, overall, the average stem height changes over time ($p < 0.1$) according to the position for each species (Fig. 3, Table 4). The lowest heights, both inside and outside of sediment patches, were reached just after storm Grayson occurred. This suggests that the storm event affected the entire marsh vegetation in terms of height. The vegetation stems outside the mud patches were probably smothered during the storm event, while fewer stems inside regrew after sediment burial killed them. Moreover, the lowest heights measured within the year indicate the presence of seedlings (Fig. 3). After the first growing season, the stem heights of *S. patens*, *D. spicata*, and *J. gerardi* measured inside the patches were significantly lower than those measured outside ($p < 0.1$) (Fig. 3a,b,d). The mean height inside the patches recovered after the second growing season and stayed slightly higher than outside over the next years. This increase was more significant for *S. patens* stems, which reached values inside the patches 5–10% higher than outside over time (Fig. 3a), suggesting a positive effect of sediment burial on *S. patens* growth along some transects. The positive effect is better analyzed for each individual patch (Figs. S7–S12, Tables S5–S8). Two-way ANOVA results indicated that *S. patens* stem heights inside the patches recovered in 2 growing seasons in most transects. After the recovery, statistical results confirmed that the average stem heights inside the plots remained stable and/or higher than the average heights outside the

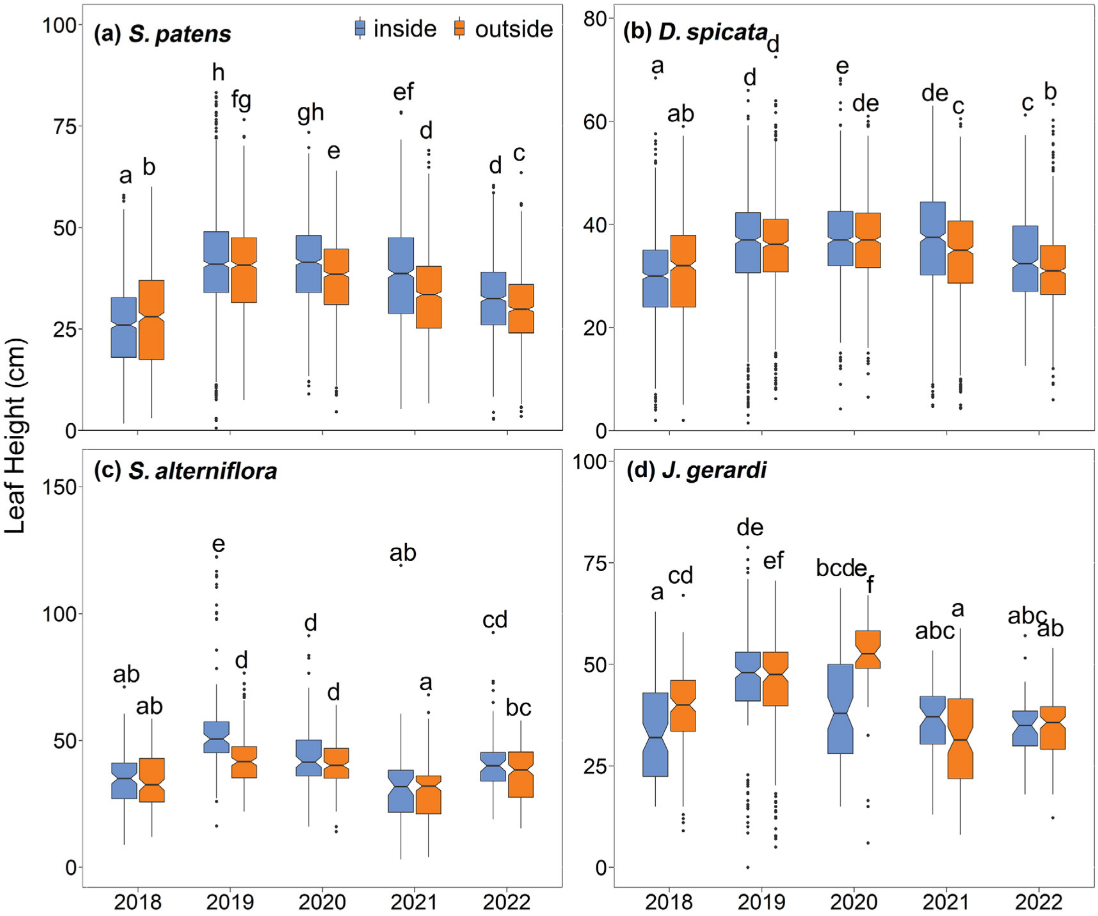

Fig. 3. Heights of all (a) *Spartina patens*, (b) *Distichlis spicata*, (c) *Spartina alterniflora*, and (d) *Juncus gerardi* stems inside and outside of sediment patches deposited by ice rafts in the study area over time. Black line inside each box: median of the dataset for each year and position; height of the box: interquartile range; whiskers: variability of the data outside the lower and the upper quartiles; black points: outliers of the dataset. Letters over the boxes identify post-hoc Tukey test results ($\alpha = 0.1$)

plots (Figs. S7, S8, S10–S12). The presence of wrack in 2021 lowered the inside mean stem height in transects 1A and 13 by about 40% (represented by a black star in Fig. S7) but did not affect transects 8, 10, and 16 (Figs. S7a,b & S12c,o). Similar to *S. patens*, after recovery the stem height of *D. spicata* inside the patch remained higher than outside (Fig. S7). Wrack presence in transect 1A affected the calculated mean stem height, with a decrease around 10% when compared to undisturbed conditions (Fig. S7), confirming the low sensitivity of *D. spicata* to wrack. *S. alterniflora* stem heights inside did not differ from outside after the storm event (Fig. 3c), suggesting that overall, this species was not affected by sediment deposition in terms of stem height. Despite the overall results, in transects 6 (Fig. S9) and 3 (Fig. S10), the *S. alterniflora* height seemed to be affected by sediment deposition, and its recovery occurred after 2 growing seasons. In transects 2B and 14, no differences between inside and outside were detected over time, based on the overall analysis (Fig. S11).

Wrack presence in 2021 did not affect *S. alterniflora* stem height in transect 6 (Fig. S9). Table 5 summarizes the difference in stem height between inside and outside for each patch to better visualize vegetation recovery and the beneficial effect on growth.

3.3. Water content, specific conductivity, and temperature

Edaphic conditions inside a representative sediment patch dominated by *S. patens* and *D. spicata* were more favorable to vegetation during the measured period. Water content values outside and inside the patch were 0.63 and 0.64 $m^3\ m^{-3}$ on average, respectively (Fig. 4a). Equal temperature values were measured outside and inside the plot (Fig. 4b). On

Table 4. Summary results of 2-way ANOVA model for all heights of each species outside and inside of sediment patches deposited by ice rafts: heights~position+year+position:year. Position and year are main effects, and position:year represents the interaction. Other details as in Table 3

Effect			Position		
Test	df	Mean of squares	F	F_{crit}	p
Species					
Spartina patens	1	11412	**89.29**	2.72	**$<2.20 \times 10^{-16}$**
Distichlis spicata	1	688	**7.34**	2.72	**6.77×10^{-3}**
S. alterniflora	1	8674	**50.34**	2.73	**2.18×10^{-12}**
Juncus gerardi	1	60.9	0.34	2.73	0.56
Effect			Year		
Test	df	Mean of squares	F	F_{crit}	p
Species					
S. patens	4	56500	**442.10**	1.96	**$<2.20 \times 10^{-16}$**
D. spicata	4	12264	**130.72**	1.96	**$<2.20 \times 10^{-16}$**
S. alterniflora	4	12139.50	**70.45**	1.98	**$<2.20 \times 10^{-16}$**
J .gerardi	4	5150.80	**28.82**	1.98	**$<2.20 \times 10^{-16}$**
Effect			Position:Year		
Test	df	Mean of squares	F	F_{crit}	p
Species					
S. patens	4	3185	**24.92**	1.96	**$<2.20 \times 10^{-16}$**
D. spicata	4	990.80	**10.56**	1.96	**1.58×10^{-8}**
S. alterniflora	4	1666.60	9.67	1.98	**1.06×10^{-7}**
J. gerardi	4	1267.80	7.09	1.98	**1.24×10^{-5}**

average, lower water content is correlated with a higher conductivity value. Specific electrical conductivity values were higher outside the plot compared to inside (Fig. 4c). In particular, mean inside electrical conductivity was around 25 mS cm^{-1} while outside it was around 35 mS cm^{-1} over the period of data collection. *t*-tests performed on variables inside and outside revealed a significant difference between water content and specific conductivity (t [68.7] > t_{crit} [1.65] for water content and t [58.2] > t_{crit} [1.65] for conductivity, $p < 0.05$) (Fig. 4a,c).

4. DISCUSSION

Ice-rafted sediment deposition occurred on Plum Island on 4 January 2018, significantly affecting marsh vegetation. Mud patches between 2 and 5 cm thick smothered marsh vegetation, but significant plant regrowth after sediment deposition was confirmed by our measurements. The number of stems measured inside sediment patches was lower than measured outside after the first growing season. After 2 growing seasons, the number of stems inside the patches reached values similar to the control plots. These results are in accordance with data presented by Wittyngham et al. (2022) and Moore et al. (2021). Wittyngham et al. (2022) analyzed data collected in May 2018, after winter storm Grayson, and in August 2018 and August 2019. They similarly measured the number of stems in the sediment patches and expanded their research to infauna and epifauna species. Their results suggested that by August 2018, approximately 6 months following sediment deposition from storm Grayson, there was no statistically significant difference in plant communities between areas with sediment deposits and reference plots, indicating a full recovery. The number of stems inside the sediment patch equaled the number of stems outside approximately 18 mo after the storm event. Similar results were obtained for density of stems and biomass. Using visual estimation methods, Moore et al. (2021) showed that the deposited sediment reduced plant cover by 17% in the short term, but plants fully recovered within 1–2 growing seasons. Our research integrates, confirms, and expands the results observed in these 2 previous studies, concentrating on a longer data set.

In our study, results from the overall analysis suggest a full recovery of the number of stems after 2 growing seasons for *Spartina patens*, but in some patches, the recovery time was faster. In contrast, we saw no significant difference in *Distichlis spicata* and *Juncus gerardi* over the years. In many transects, the number of stems and stem height were higher inside the plots after 3 yr. Therefore, a study limited to 2 yr may capture the recovery period, but it is not sufficient to characterize the beneficial effects of sediment deposition on vegetation. This effect was mostly assessed using stem heights, which were not considered in previous studies.

Vegetation regrowth is also fundamental for water velocity reduction. In bare soils, erosion due to water flow is higher than in vegetated areas, where the friction coefficient is higher and flow velocities are consequently reduced (Rinaldo et al. 1999b, Nepf & Vivoni 2000, Leonard & Croft 2006). As both vegetation height and density increase, the sedimentation rate increases, positively influencing marsh accretion and allowing marshes to keep

Table 5. Post hoc multi-comparison results from 2-way ANOVA test for stem height inside vs. outside of sediment patches deposited by ice rafts. NA: data not available

			Inside vs outside= 🟨 No difference, 🟩 higher, 🟥 lower, W=wrack																	
			TRANSECT																		
			1A	1B	2A	2B	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
S. patens	YEAR	2018	🟨	🟨	🟥	NA	NA	🟨	🟨		🟥	🟩	🟨	NA	🟨	🟨	🟥	🟥	NA	🟩	🟩
		2019	🟨	🟩	🟩	NA	🟨	🟥	🟨		🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟥	🟩	🟩	🟥
		2020	🟨	🟨	🟩	NA	🟨	🟨	🟩		🟨	🟨	🟨	NA	🟨	🟩	🟨	NA	🟩	🟩	🟨
		2021	🟨 W	🟥	🟩	NA	🟩	🟩	🟨		🟨	🟩 W	🟥	🟨	🟩	🟩	🟩 W	🟨	🟩 W	🟥	🟩
		2022	NA	🟨	🟨	NA	🟨	🟨	🟥 W		🟨	🟩	🟨	🟨 W	🟨	🟩	🟨	🟥	🟩	🟨 W	🟩
D.spicata	YEAR	2018	🟨	🟨	🟨	NA		🟨			🟥		🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩	🟩
		2019	🟨	🟨	🟩	NA		🟨			🟨		🟨	🟨	NA	🟨	🟨	🟨	🟨	🟩	🟨
		2020	🟨	🟨	🟩	NA		🟩			🟥		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
		2021	🟩	🟨	🟨	NA		🟨		W	🟨	W	🟨	🟨	NA	🟩	🟩 W	🟨	🟩 W	🟨	🟩
		2022	NA	🟨	🟨	NA		🟨	W		🟨		🟩	🟨 W	🟨	🟩	🟨	🟩	🟩	🟨 W	🟨 W
S.alterniflora	YEAR	2018				🟨	NA			🟥								🟨			
		2019				🟨	🟩			🟩								🟨			
		2020				🟨	🟩			🟩								🟨			
		2021	W			🟥	🟩			🟨 W							W	🟩			
		2022	W			🟩	🟩	W		🟨 W				W				🟨			W
J.gerardi	YEAR	2018												🟩	NA	NA			NA	NA	
		2019												🟨	🟨	🟥			🟨	🟩	
		2020												🟥	🟨	🟨			NA	🟨	
		2021	W							W		W		NA	🟨	🟨	W		🟩 W	NA	
		2022	W					W	W					🟥 W	🟨	🟨			🟨	NA	W

pace with sea level rise (Temmermann et al. 2005).

The beneficial effect of sediment deposition agrees well with previous research in salt marshes. Baustian & Mendelssohn (2015) indicated that recovery rates and primary production increased with the thickness of sediment deposited by hurricanes in Barataria Bay, Louisiana, USA. They justified their results by analyzing physicochemical conditions resulting from sedimentation, such as the delivery of nutrients to the marsh and the reduction of sulfide concentration. Sediment deposition created a more oxidized soil environment; it reduced sulfide concentrations and increased phosphorus amounts and exchangeable soil iron and manganese concentrations. Mendelssohn & Kuhn (2003) estimated the effect of a sediment slurry (85 % liquid and 15 % solid) — accidentally overflowing onto the saltmarshes in the Mississippi River Delta — on *S. alterniflora* growth. Statistical analysis suggested a significant increase in the total cover percentage and stem heights where sediment thickness was higher. Deng et al. (2008) showed a significant positive effect of different sediment burial rates on the height and number of *S. alterniflora* stems. Plant recovery was determined by the instantaneous thickness of sediment of each burial event.

The effect of ice-raft sedimentation on marsh vegetation is significantly higher than the effect of storm surge events and tides that normally affect the study site. Stopak et al. (2022) estimated an accretion of 0.57 ± 0.14 mm yr^{-1} due to ice-raft sediment accounting for 20 % of the total annual accretion in the Plum Island marshes. Locally, a sediment thickness of 2.9 cm on average was 8–14 times higher than the annual sediment thickness, mainly brought by tides and storm surges. Sediment deposition due to ice-raft debris during winter storm Grayson was estimated as the equivalent of 12–15 yr normal deposition (FitzGerald et al. 2020, Stopak et al. 2022, Wittyngham et al. 2022). The vegetation was mostly buried after the event, and a reduced number of stems and shorter heights were measured inside the patches at the

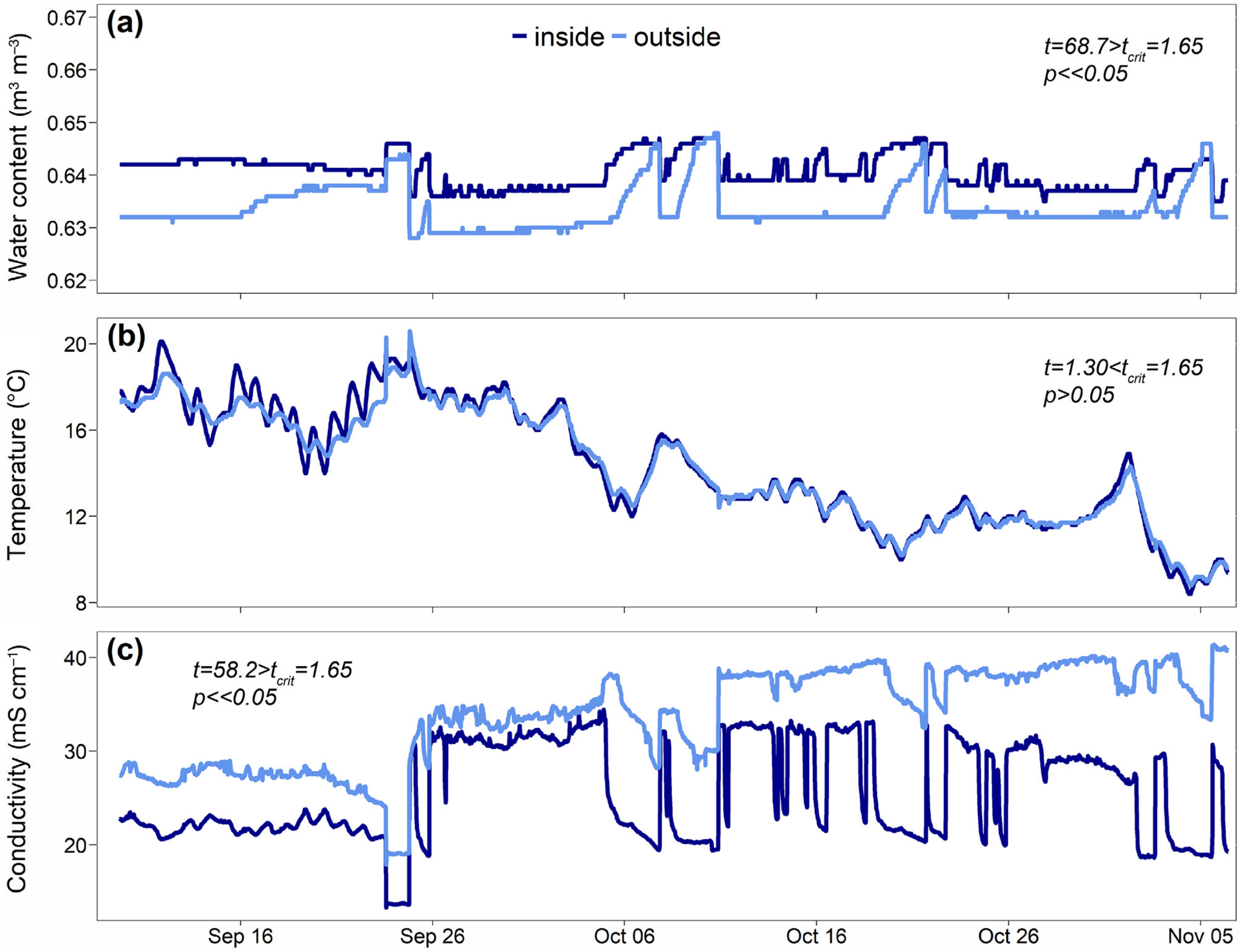

Fig. 4. (a) Water content, (b) temperature, and (c) specific conductivity data collected outside and inside one sediment patch as reference. Significance: $\alpha = 0.05$. t_{crit}: critical t-value to which the obtained t-values were compared

end of the first growing season. Over the next years, high tides and storm events did not have a significant effect on the number of stems for each species. This justifies the extension of the research to a longer period.

Although vegetation heights measured inside the patches were lower than outside in 2018, it is likely that the entire vegetation canopy was affected by the storm event. Johnson et al. (2016) measured average shoot heights of 35 and 40 cm for *S. patens* and *D. spicata*, respectively, in control plots in Plum Island sound. These values are similar to the stem height we measured outside the patches from 2019 to 2022, while in 2018 we measured lower values. Johnson et al. (2016) also calculated stem density of *S. patens* in control plots to be on average 9000 stems m^{-2}. A similar result was shown by Buchsbaum et al. (2008), who measured stem density to be around 6000 stems m^{-2} for *J. gerardi* and around 2000 stems m^{-2} for short- and medium-form *S. alterniflora*. In our plots, we measured a slightly lower stem density for the same species. This difference could be ascribed to different geographic locations and data collection periods. Johnson et al. (2021) and Buchsbaum et al. (2008) collected data during the growing season, while we collected data at the end of the growing season. Overall, we assume that the storm event had a stronger impact on vegetation growth during the subsequent summer, leading to shorter vegetation height, while the ice-rafted sediment deposited on the marsh platform killed or buried most of the vegetation stems (Figs. 2 & 3). At the same time, this large amount of sediment brought nutrients, facilitating a fast vegetation recovery.

Mendelssohn & Kuhn (2003) collected soil salinity data as a function of sediment thickness deposited on the marsh. Soil salinity increased when sediment thickness was higher than 15 cm, with no significant difference for a sediment thickness lower than 15 cm. Moore et al. (2021) measured edaphic conditions in terms of porewater salinity, redox potential, and pH for plots affected by different ranges of sediment thickness between 1 and 90 mm. In contrast with our results, they did not find significant differences between porewater salinity inside and outside sediment patches. This can be ascribed to the sampling method used and to the slightly different variables measured. Favorable salinity and water content conditions positively influence the growth of vegetation species (Pennings & Callaway 1992) and support taller stem heights over the years. Our data of water content, temperature, and specific conductivity suggest more water content and less conductivity below sediment patches once plant recovery is over. The soft and porous sediment deposited by ice rafts better collects rainfall, and therefore increases soil water content and reduces conductivity. The typical soil of the marsh is more compacted, and therefore cannot store the freshwater rainfall, leading to harsher conditions for vegetation. This effect is more evident in high marshes dominated by *S. patens*, where sporadic tidal flooding occurs only during very high spring tides. In lower marshes that are flooded daily by saline water, rainfall likely has a limited effect on edaphic conditions. This explains the results of Mendelssohn & Kuhn (2003), who found an increase in salinity with sediment thickness in low *S. alterniflora* marshes.

Natural disturbances like ice-rafted sediment deposition play an important role in marsh plant community dynamics. Large amounts of mud can smother the dominant vegetation, leaving room for the encroachment of fugitive species. In the high marshes of our study site, *D. spicata* first invades the hypersaline bare patches (Bertness 1991, Pennings & Bertness 2001). The initial invaders facilitate the recovery of the dominant species, shading the soil and lowering the hypersaline conditions of the bare patch, thus creating a suitable habitat for less salt-tolerant but more competitive plants. Bertness & Ellison (1987) estimated that, within 3–4 yr after a natural disturbance, *D. spicata* was competitively displaced by zonal dominants. Facilitation and competition were defined as the driver of the interactions between identical species under different environmental conditions (Bertness & Shumway 1993). Our results confirm the dynamics previously described. In the area dominated by *S. patens*, *D. spicata* occupied bare patches just after the storm event, and its number of stems remained stable when *S. patens* regrew. Where the soil conditions in the high marsh are anoxic, *S. alterniflora* dominates. Sediment deposition killed a larger percentage of *S. alterniflora* in transect 2B and smothered vegetation in transect 6. An increase in elevation due to sediment deposition was sufficient to encourage *D. spicata* invasion in transects 2B and 3, facilitating *S. patens* future establishment. In transect 6, *S. alterniflora* was able to recover. The different dynamics could be due to the positions of the transects. Transect 6 is far from the channels and borders a pond. Here the soil conditions are harsher due to the waterlogging effect and salinity, demonstrated by the presence of forb pannes (Ewanchuk & Bertness 2004). *S. alterniflora* is the only species able to survive here (Pennings & Bertness 2001), and a 4 cm increase in elevation due to sediment deposition is not sufficient to encourage the establishment of new species.

Wrack disturbance is very common in high marshes (Pennings & Bertness 2001). Large amounts of dead *S. alterniflora* stems are moved from the low marsh by storm surges and kill the vegetation once they are deposited on the high marsh. The effect of wrack occurrence in our plots was limited in comparison to ice-rafted sedimentation. This is because only a few plots were disturbed by wrack. Overall, our results suggest a limited wrack effect on *D. spicata* and *S. alterniflora*, as also indicated by Hartmann et al. (1983) and Bertness & Ellison (1987). Bertness & Ellison (1987) and Tolley & Christian (1999) estimated that vegetation recovery from wrack deposition occurs in 1–3 yr as a function of duration of coverage and wrack thickness, vegetation species, and edaphic conditions. Overall, vegetation species affected by wrack show similar recovery periods as with ice-rafting, suggesting similar effects on the marsh zonation dynamics.

Sediment availability is fundamental to marsh survival. Marsh accretion must keep pace with sea level rise (Crosby et al. 2016, Liu et al. 2021), particularly along the North Atlantic coast where sea level rise is accelerating (Sallenger et al. 2012). Ice-rafted sedimentation associated with winter storm Grayson was estimated to be equivalent to 12–15 yr of marsh accretion within the patches (Stopak et al. 2022, Wittyngham et al. 2022). The frequency of cold spells in the high and middle latitudes might increase due to Artic amplification (FitzGerald et al. 2021). These events combined with higher water levels encourage ice-rafted sediment deposition and promote marsh accretion. Therefore, although ice-rafted deposition initially smothers vegetation, the positive effects on marsh accretion outweigh the immediate negative effects.

5. CONCLUSIONS

Salt marsh vegetation was smothered after ice-rafting sediment deposition during winter storm Grayson in January 2018. Marsh vegetation fully recovered in terms of both number of stems and stem height within 3 growing seasons. *Distichlis spicata* first expanded on the bare patches, increasing its number of stems per square meter. *Spartina patens* stem density increased over the years, outcompeting *D. spicata*.

Once vegetation regrowth was completed, the average stem height was higher within the sediment patches. The sediment layer had a positive effect on edaphic conditions, reducing salinity levels in the soil. Sediment deposition by ice rafts, although negatively affecting vegetation in the short term, was beneficial for plant vigor in the long term.

S. alterniflora was the most affected by sediment deposition and did not regrow in 2 transects out of 3. Along these transects, the deposition of several centimeters of sediment was enough to permanently switch the vegetation to *S. patens* and *D. spicata*. *J. gerardi* was not affected by ice-raft sediment deposition.

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