Recovery of salt marsh vegetation after ice rafting

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Abstract

Sediments are usually transported on salt marsh platforms by 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 Greyson hit the North Atlantic coast, producing a large storm surge and a significant decrease in temperature. The Great Marsh in Plum Island Sound, Massachusetts, experienced an unprecedented sediment deposition due to ice-rafting, burying marsh vegetation. Plant vegetation recovery was investigated in seventeen sediment patches, dominated by *Spartina patens*, *Distichlis spicata, Juncus gerardi* and *Spartina alterniflora*. The analysis was carried out considering number of stems and stem height for each vegetation species. *Distichlis spicata* firstly occupied bare patches, while *Spartina patens*, once smothered by sediment, regrew slowly. Number of stems of *Spartina patens* inside the sediment patches recovered, on average, after two growing seasons. *Juncus gerardi* number of stems was not significantly affected by ice-rafted sediment deposition. *Spartina alterniflora* dynamics were different depending on physical and edaphic conditions. At some locations *Spartina 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 stems density. The results suggest the beneficial effect of sediment deposition not only for marsh accretion, but also for marsh vegetation growth, both fundamental for marsh restoration.

Keywords: salt marsh, salt marsh vegetation, sediment deposition, vegetation recovery, ice-rafting.

Running Header*: Marsh vegetation recovery*

Highlights:

- Sediment deposition due to ice-rafting affects salt marsh vegetation, smothering *Spartina patens*.
- Disturbed areas are rapidly colonized by *Distichlis spicata*, while *Spartina patens* recovers after two growing seasons. After this time, *Spartina patens* starts to outcompete *Distichlis spicata*. *Juncus gerardi* is not affected by sediment deposition.
- The sediment deposition has a positive effect on vegetation vigor, mainly on stem heights.

1 Introduction

Salt marshes have been long recognized for their role in coastal protection (Gedan et al. 2009, Gedan et al. 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 fast responding to both hydrological and biological drivers. They thrive when accretion rates driven by sediment transport balance sea level rise. Tidal flooding supplies marsh with sediments (Stumpf 1983, Christiansen et al. 2000) and marsh vegetation helps to trap this material (Stevenson et al. 1988, Boorman et al. 1988). 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, like 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 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 and Fitzgerald, 2006, Argow et al. 2011). Once deposited, ice-rafted sediment layers are hard to remobilize. In January 2018, winter storm Greyson hit the North Atlantic Coast, causing ice-draft deposition at an unprecedented scale in the Great Marsh of Massachusetts (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. 2021). 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). Number of vegetation stems and biomass were used to estimate plant regrowth after Greyson (Wittyngham et al. 2021). 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 and 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 study *Spartina patens*, *Distichlis spicata, Juncus gerardi* and *Spartina alterniflora* regrowth after sediment deposition due to ice rafting and their consequent inter-specific competition. The updated taxonomy of the *Spartina alterniflora* and *Spartina patens* species is respectively *Sporobolus alterniflorus* and *Sporobolus pumilus*, but we choose to use the older name for consistency with previous published work. *Spartina patens* dominates the high marsh in Massachusetts, USA, and is unable to persist in the frequently flooded low marsh area (Bertness 1991). *Juncus gerardi* is mostly present along the terrestrial border. *Distichlis 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 *Spartina patens*. According to Bertness (1991), *Distichlis spicata*, vegetatively expands on long adventitious rhizomes, and it is the first to invade bare patches. In time, it is replaced by *Spartina patens,* characterized by denser turf and *Juncus gerardi* in the marsh areas where these species are dominant (typically after 2-4 years). The cordgrass, *Spartina alterniflora*, dominates the low marsh habitats because it is able to oxygenate its rhizosphere in anoxic soils (Bertness 1991). In absence of neighboring competitors, *Spartina 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 *Spartina alterniflora* in short and tall form accordingly to their location (Shea et al. 1975). Tall *Spartina 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 focus on two parameters to describe vegetation recovery: number of stems per square meter for each vegetation species and stem height. We estimate how much time each vegetation species has needed to recover after the Grayson ice-rafting event, and whether sediment deposition could help vegetation regrowth. Wittyngham et al. (2021) conducted a similar study concentrating on plant and invertebrate community regrowth over 18 months after the same event. Our study is longer in duration and concentrates on plant communities.

2 Methods

In the Great Marsh, seventeen sediment patches deposited by ice rafts were identified in February 2018 (Fig. 1). Latitude, longitude and elevation data of each patch were collected using a TOPCON Real-Time Kinematic GPS system (Table 1). Spatial coordinates were referred to the midpoint of each patch, while the elevation inside and outside the patch was calculated as average of plot elevation inside and outside along the transect. Patch area was calculated in QGIS using coordinates of patch boundary. Mud layer thickness was measured from sediment samples using a caliper (Table 1) (Stopak et al. 2022). Sediment samples were analyzed using wet sieving (Robertson et al. 1984) to separate sand and silt/clay fractions. Approximately 50 cc of each sediment sample was first sonicated for 15 minutes at room temperature (~24°C) in a beaker, filled with 100 cc of water, to separate aggregated particles. Fine sediment was then separated from course sediment using sieves of 10µm, 63µm and 230µm. Coarser material retained in the 10µm sieve is classified as 'debris and vegetation'. Sediments was dried at a temperature of 60°C. Finally, once weighed, the percentage of fine and course material was calculated. In addition, undisturbed samples were collected to calculate the percentage of organic matter (OM). They were dried as the previous ones, grained and put in a furnace at 375°C (loss on ignition). In Table 2 results for each patch are reported. Six patches were dominated by *Spartina patens* and *Distichlis spicata,* two exclusively by *Spartina patens*, five were occupied by *Spartina patens*, *Distichlis spicata* and *Juncus gerardi* and four by *Spartina alterniflora*. In each patch, vegetation data were collected along a transect, within squared plots. Three stations were established inside the sediment patch and three outside in the undisturbed area as control. A 25-cm quadrat was exactly placed at the same location every year, using a permanent PVC pole for reference, with the top-most point of the quadrat oriented north with a compass. The vegetation stems for each species inside each plot were counted. The growing season of these species is between late spring and summer. The height of twenty randomly chosen vegetation stems were 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 in both outside and inside plots. A two-way ANOVA analysis with interaction followed by a post-hoc Tukey test was performed to evaluate significant differences between average number of stems and heights inside and outside sediment patches over years.

Significance level is set to 90% to guarantee a good balance between sample size and statistical analysis power. For some patches, due to the small size of the dataset, the statistical results can be misleading (Cohen 2013). In 2021 and 2022, the presence of dead biomass in each plot (wrack) was recorded. Wrack usually consists of *Spartina alterniflora*. Plants in the New England marshes grow from May to September, in the late fall they reallocate all 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 and Bertness, 2001).

Two soil moisture sensors TEROS, by METER, were installed inside and outside patch 10 dominated by *Spartina patens* and *Distichlis spicata*. This patch was selected because sufficiently far away from channels and ponds. Therefore, we can suppose that eventual data differences in edaphic conditions can be attributed to the presence of the mud layer rather than 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 minutes from September 2019 to November 2019, once the number of stems recovery occurred. These data are used to correlate long-term ecological patterns to soil properties. An unpaired t-test with significance level of 5% is finally used to statistically compare water contents, temperatures, and electrical conductivities outside and inside the patches.

All the statistical analysis are done using R– 4.2.2 for Windows and R-studio 2022.12.0+353. Libraries *stats*, *lmeans* and *multcomp* are used to perform *t*-test, ANOVA and post-hoc Tukey tests.

3 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 32x10^6 m^3 (Vallino and Hopkinson, 1998, Farron et al. 2020). Farron et al. (2020) defined four 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 January 4, 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 on MSL, with a storm surge of 2 m. A sediment volume equivalent to 12/15 years of marsh accretion was deposited at some locations in the Great Marsh, through ice-rafts (Wittyngham et al. 2021, Stopak 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 marsh platform is around few centimeters or even lower at the highest elevations according to NOAA station id:8447930). Because of this, the ice-sheet transporting sediment layers, deposited and melt at the same location, not being subjected to refloating.

4 Results

4.1 Stem number

An overall analysis of *Spartina patens*, *Distichlis spicata, Juncus gerardi* and *Spartina alterniflora* stems inside and outside the patches is presented in Fig. 2. In February 2018, right after the storm event, patches were bare and consisting of 80-90% of 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 in the outside plots, considered as reference values. Two-way ANOVA results suggest a significant difference of *Spartina patens* stems over the years and accordingly to position ($p<0.1$) (Table 3). In particular, stems inside the patches are 70% significantly less dense than outside after the first growing season ($p<0.1$). In 2019, number of stems inside the patches recovers ($p>0.1$), reaching values 20% lower than outside. After 2 growing seasons, the growth is regulated by other disturbances (e.g. wrack) and inter-species competition. After the storm surge event, in September 2018, *Distichlis spicata* rapidly colonized the bare patches (Fig. 2b). The total number of *Distichlis spicata* stems does not significantly differ between inside and outside the patches over the years (Fig. 2b, Table 3) ($p>0.1$), even if we detect a slightly higher density inside the patches. Two-way ANOVA results show a significant difference of *Spartina alterniflora* stem density between outside and inside (Table 3-Fig.2c) ($p<0.1$). Although the difference between inside and outside each patch after the first growing season is not statistically significant, due to the smaller dataset size, stems inside are 60% less dense than outside. The number of stems inside the patches remains quite constant and lower than outside over the next years (Fig. 2c). The number of stems of *Juncus gerardi* did not differ in position and over the years (Fig. 2d, Table 3) ($p>0.1$).

In Fig. S1, S2, S3, S4, S5, S6 (Supplementary material) the mean number of stems for each transect from September 2018 to October 2022 is shown. Table S1, S2, S3, S4 (Supplementary material) summarize the two-way ANOVA results for each transect. The analysis confirms the results obtained in the overall study for *Spartina patens* and *Distichlis spicata*. The post-hoc test results, reported on the bar plots (letters) 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 *Spartina patens* inside the patches reached the number outside after two growing seasons in the transects, outcompeting *Distichlis spicata* (Fig. S1, S2, S6 Table S1-S2). After recovery, in transects 1A, 4, 7, 8, 12 and 17, *Spartina patens* number of stems inside reached values slightly higher than outside, suggesting the beneficial effect of sediment deposition on *Spartina patens* growth. This effect can also be detected for *Distichlis spicata* in the overall analysis and confirmed looking at single patch (Fig. 2b, Fig S1, S6). Sediment deposition had a different effect in patches dominated by *Spartina alterniflora* (Fig. S3, S4, S5- Table S3). In transect 6 (Fig. S3), the number of stems of short form *Spartina alterniflora* was similar over the years and between outside and inside the patch. In transect 3 (Fig. S4) the number of stems of tall form *Spartina alterniflora* inside the patch was 55% lower than outside after the first growing season and tended to slightly decrease over the years (Fig. S4 b). As consequence of sediment deposition, increasing elevation (Table 1), *Spartina patens* invaded the bare patch, with a number of stems quite constant over the following years (Fig. S4 a). In transect 2B, after the storm, the stem number of short-form *Spartina alterniflora* drastically decreased (80% lower) and never recovered (Fig. S5c). *Distichlis spicata* occupied bare patches after the first growing season (Fig. S5 b), but *Spartina patens* density kept increasing, outcompeting the fugitive species (Fig. S5 a). In transect 14, *Spartina alterniflora* was not affected by sediment deposition, and the number of stems remained constant over the years.

The presence of wrack, detected in October 2021 and September 2022, influenced the average values of that year in many plots (Fig. S1a-b, Fig. S2b, Fig S6 a-b-c-o-p-q,), reducing the number of stems. By considering only plots where wrack is 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 *Spartina patens* stems between

10% and 60% compared to the undisturbed plots (dotted line in Fig. S1a, S2b, Fig S6 a-o,), inhibiting growth by reducing light levels and providing a physical barrier to plant emergence. The number of stems of *Distichlis spicata, Juncus gerardi* and *Spartina alterniflora* is less sensitive to wrack deposition (Fig. S1b, S3, S6 b-c-p-q).

4.2 Stem height

Results of two-way ANOVA suggest that, overall, the average stem height changes through the years ($p<0.1$) accordingly to the position for each species (Fig.3- Table 4). The lowest heights, both inside and outside, were reached just after storm Greyson occurred. This suggests that the storm event affected the entire marsh vegetation in terms of heights. The vegetation stems outside the mud patches were probably smothered during the storm events, while the fewer stems inside regrew once sediment burial killed them. Moreover, the lowest heights measured within the year indicate the presence of seedling (Fig. 3). After the first growing season, the stem heights of *Spartina patens*, *Distichlis spicata* and *Juncus gerardi* measured inside the patches are significantly lower than those measured outside ($p<0.1$) (Fig. 3a-3b). The mean height inside the patch recovers after the second growing season and stays slightly higher than outside over the years. This increase is more significant for *Spartina patens* stems, that reach values inside the patches 5%-10% higher than outside over the years (Fig. 3a). This suggests a positive effect of sediment burial on *Spartina patens* growth along some transects. The positive effect is better analyzed for each single patch (Fig. S7-S12, Table S5-S8 (Supplementary material)). Accordingly, to two-way ANOVA results, *Spartina patens* stem heights inside the patches recover in 2 growing seasons in most transects. After the recovery, statistical results confirmed that the average stem heights inside the plots remain stable and/or higher than the average heights outside the plots (Fig.

S7-S8,S10-S12). The wrack presence in 2021 lowers the inside mean stem height in transect 1A and 13 of about 40% (represented by a black star in Fig. S7) but does not affect transect 8, 10 and 16 (Fig. S7a b, S12 c,o). Similarly, to *Spartina patens*, after recovery the stem height of *Distichlis spicata* inside the patch remains higher than outside (Fig. S7). Wrack presence in transect 1A affects the calculated mean stem height, with a decrease around 10% if compared to undisturbed conditions (Fig. S7). This confirms the low sensitivity of *Distichlis spicata* to wrack. *Spartina 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 transect 6 (Fig. S9) and 3 (Fig. S10), the *Spartina alterniflora* height seems to be affected by sediment deposition and its recovery occurred after two growing seasons. In transect 2B and 14 no differences between inside and outside are detected over the years, accordingly to the overall analysis (Fig. S11).

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

4.3 Water content, specific conductivity and temperature

Edaphic conditions inside a sediment patch dominated by *Spartina patens* and *Distichlis spicata* are more favorable to vegetation during the measured period. Water content values outside and inside the patch, are respectively of 0.63 and 0.64 m^3/m^3 on average (Fig. 4a). Equal temperature values are measured outside and inside the plots (Fig. 4b). On average, a lower water content value matches a higher conductivity value. Specific electrical conductivity values are higher outside the plot compared to inside (Fig. 4c). In particular, mean inside electrical conductivity is around 25 mS/cm while outside is around 35 mS/cm over the period of data collection. *t*-test performed on variables inside and outside, suggests 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).

5 Discussion

Ice-rafted sediment deposition occurred in Plum Island on January 4, 2018, significantly affecting marsh vegetation. Mud patches of thickness between 2 and 5 cm smothered marsh vegetation. A significant plant regrowth after sediment deposition was confirmed by our measurements. Number of stems measured inside sediment patches was lower than those measured outside after the first growing season. After two growing seasons, the number of stems inside the patches reached similar values of the control plots. These results are in accordance with data presented in Wittyngham et al. (2021) and Moore et al. (2021). Wittyngham et al. (2021) analyzed data collected in May 2018, after Greyson storm, August 2018 and August 2019. They similarly measured 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 winter storm Greyson, there was no statistically significant difference in plants community 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 months after the event. Similar results were obtained for density of stems and biomass. Moore et al. (2021), using visual estimation methods, 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 expanded the results observed in these two previous works, concentrating on a longer dataset.

In our study, results from the overall analysis suggest a full recovery of number of stems after two growing seasons for *Spartina patens*, but in some patches the recovery time was faster. On the contrary, we saw no significant difference in *Distichlis spicata* and *Juncus gerardi* over the years. In many transects number of stems and stem height were higher inside the plots after three years. Therefore, a study limited to two years can 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, that 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 the flow velocities are consequently reduced (Rinaldo et al. 1999b, Nepf and Vivoni, 2000, Leonard and Croft, 2006). As both vegetation height and density increase, the sedimentation rate increases, positively influencing marsh accretion, and allowing marshes to keep pace with sea level rise (Temmermann et al. 2005).

The beneficial effect of sediment deposition well agrees 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 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, increased phosphorous 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 the saltmarshes in the Mississippi River Delta, on *Spartina 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 *Spartina alterniflora* number of stems and stem height. The 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 affecting the study site. In Stopak et al. 2022, an accretion of 0.57±0.14 mm/y due to ice-raft sediment accounting for 20% of the total annual accretion was estimated 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 Greyson storm was estimated as a 12-year/15-year normal deposition (Fitzgerald et al. 2020, Wittyngham et al. 2021, Stopak 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 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.

Despite 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 an average shoot height of 35 cm and 40 cm for *S. patens* and *D.spicata* 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 for *Spartina patens*. In control plots *Spartina patens* density was on average 9000 stems/m^2. A similar result was shown in Buchsbaum et al. (2008). Buchsbaum et al. (2008) also measured *Juncus gerardi* stem density, around 6000 stems/m^2 and short and medium form of *Spartina alterniflora* stem density, around 2000 stems/m^2. In our plots we measured a slightly lower stem density for the same vegetation species. This difference could be ascribed to geographic location and data collection period. 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 can suppose 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 (Fig. 2 and 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. There was not a significant difference for a sediment thickness lower than 15 cm. Moore et al. (2021) measured edaphic conditions in terms of pore water salinity, redox potential, and pH for plots affected by different ranges of sediment thickness between 1 mm and 90 mm. Differently from our results, they did not find significant differences between pore water 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 justify 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 the 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 *Spartina patens*, where sporadic tidal flooding occurs only during very high spring tides. In lower marshes that are flooded daily by saline water, rainfall has likely 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 *Spartina alterniflora* marshes.

Natural disturbances like ice-rafted sediment deposition play an important role in the marsh plant community dynamics. Large amounts of mud can smother the dominant vegetation species, leaving room for the encroachment of fugitive species. In the high marshes of our study site, *Distichlis spicata* first invades the hypersaline bare patches (Bertness 1991, Bertness 1992, 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 years after a natural disturbance, *Distichlis 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 area dominated by *Spartina patens*, *Distichlis spicata* occupied bare patches just after the storm event, and its number of stems remained stable when *Spartina patens* regrew. Where the soil conditions in the high marsh are anoxic, *Spartina alterniflora* dominates. Sediment deposition killed a larger percentage of *S. alterniflora* in transects 2B and smothered vegetation in transect 6. An increase in elevation due to sediment deposition was sufficient to encourage *Distichlis spicata* invasion in transect 2B and 3, facilitating *Spartina 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 bordering a pond. Here the soil conditions are harsher due to the waterlogging effect and salinity, demonstrated by forb pannes presence (Ewanchuk & Bertness, 2004). *Spartina alterniflora* is the only species able to survive here (Pennings & Bertness 2001), and a 4 cm of elevation increase due to sediment deposition is not sufficient to encourage new species establishment.

Wrack disturbance is very common in high marshes (Pennings & Bertness 2001). Large amounts of *Spartina alterniflora* dead stems are moved from the low marsh by storm surges and kill the vegetation once they deposit on the high marsh. The effect of wrack occurrence in our plots was limited in comparison to ice-rafted sedimentation. This is because only few plots were disturbed by wrack. Overall, our results suggest a limited wrack effect on *Distichlis spicata* and *Spartina 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 years as a function of duration of wrack thickness, vegetation species and edaphic conditions. Overall, vegetation species affected by wrack show similar recovery periods than 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 to winter storm Greyson was estimated to be equivalent to 12/15 years of marsh accretion within the patches (Wittyngham et al. 2021, Stopak 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 smother vegetation, the positive effects on marsh accretion outweigh the immediate negative effects.

6 Conclusions

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

Spartina alterniflora was the most affected by sediment deposition and did not regrow in two transects out of three. Along these transects, the deposition of few centimeters of sediment was enough to permanently switch the vegetation to *S. patens* and *D. spicata*. *Juncus gerardi* was not affected by ice-raft sediment deposition.

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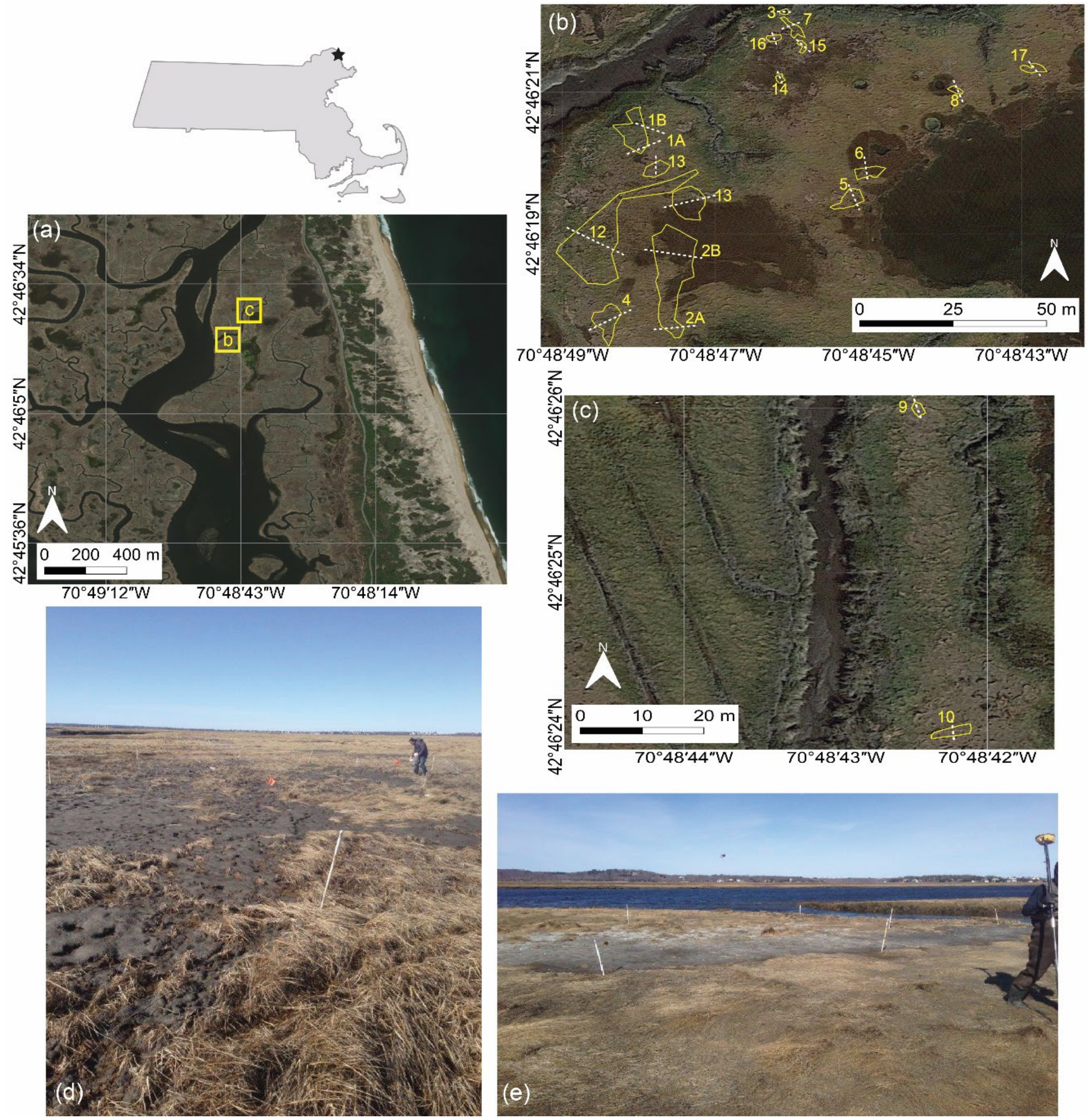

Figure 1:(a) Study site in the Great Marsh, Massachusetts USA. (b),(c) Sediment patches detected after the storm event of January 2018. The established transects are also indicated. (d), (e) Mud patches photos taken in February 2018, after storm Greyson occurred.

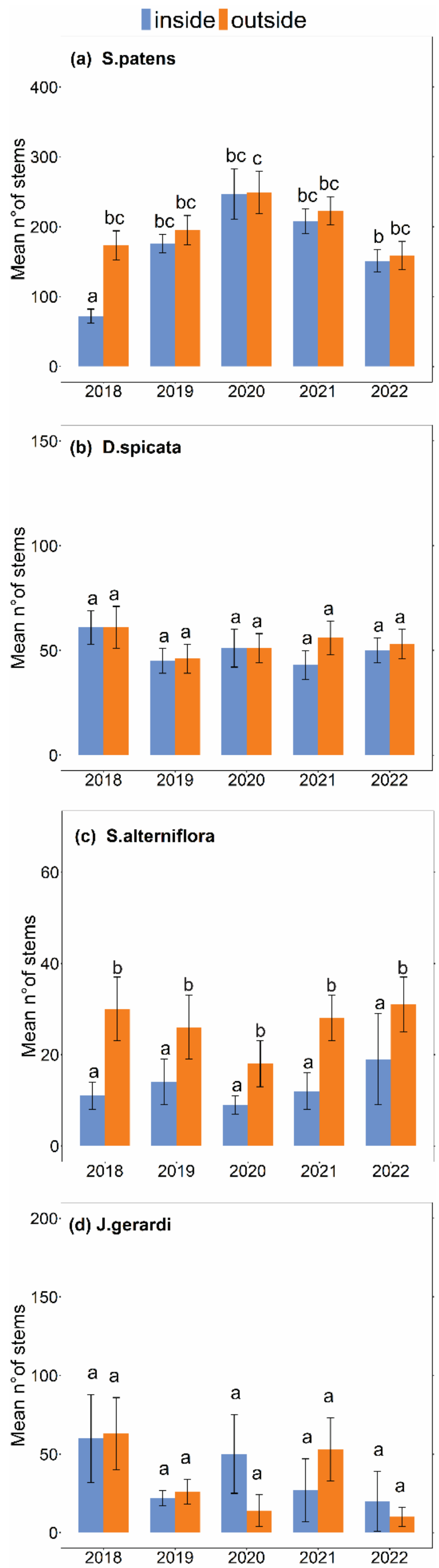

Figure 2: Total number of Spartina patens, Distichlis spicata and Spartina alterniflora stems inside and outside in the study area over the years. Letters over the bars identify post-hoc Tukey test results (significance level 10%).

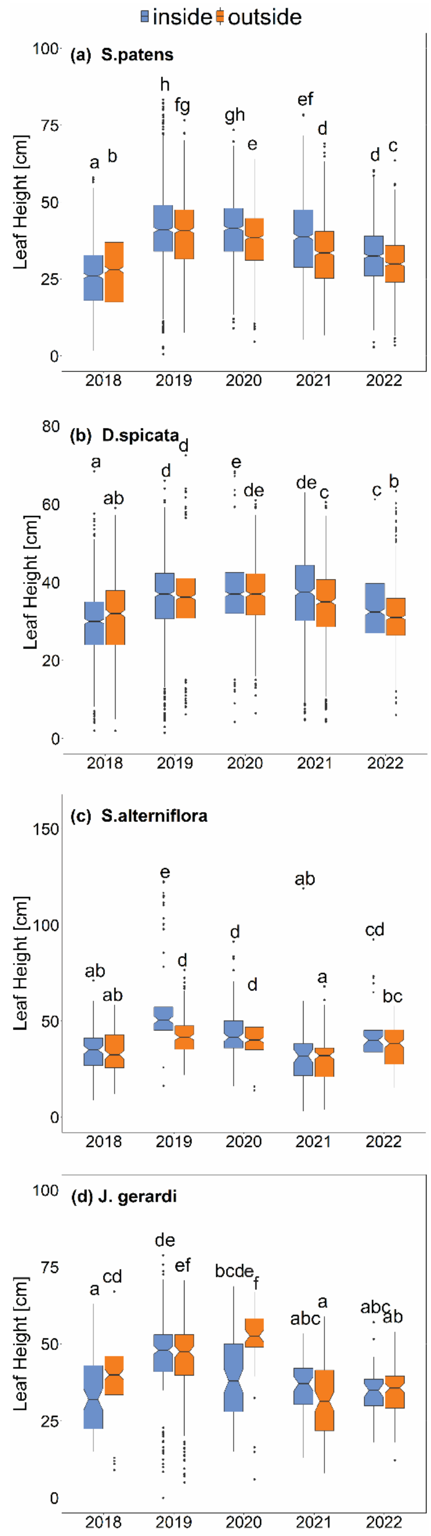

Figure 3: Heights of all of Spartina patens, Distichlis spicata and Spartina alterniflora stems inside and outside in the study area over the years. Letters over the bars identify post-hoc Tukey test results (significance level 10%).

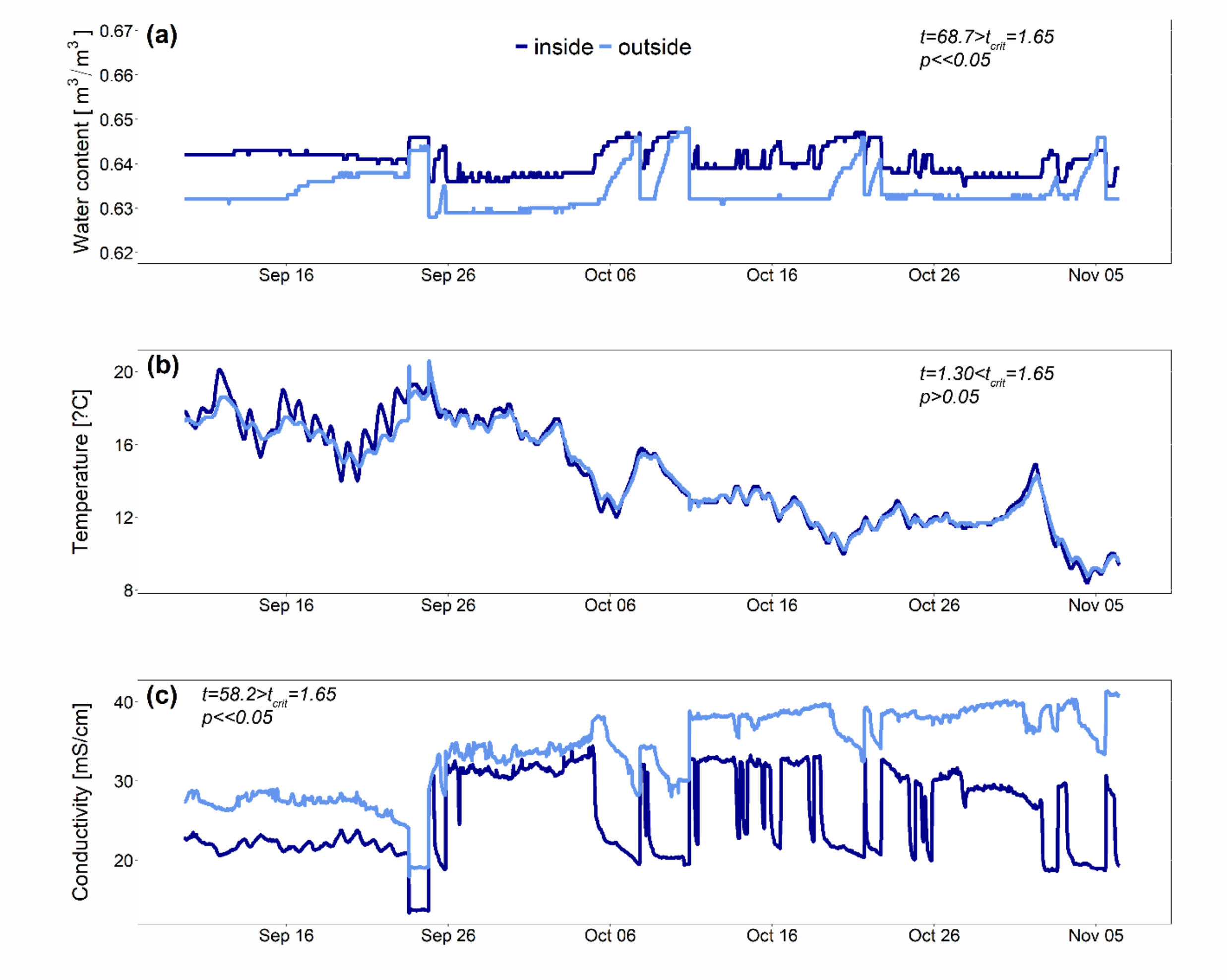

Figure 4: Water content, temperature and specific conductivity data collected outside and inside one patch as reference. In the plots p refers to the p-value (significance level 5%) and t refers to the t-value resulting from the t-test. t_{cr} is the critical t-value to which compared the t-values obtained.

Table 1: patches characteristics. Patch thickness is expressed as an average value along with its variance.

Patch	Transect #	Mean Latitude	Mean Longitude	Mean Elevation on NAVD88 (m) outside	Mean Elevation on NAVD88 (m) inside	Distance from channel (m)	Patch area (m^2)	Patch thickness along transect (cm)
1	1A	-70.8132	42.7723	1.37	1.39	12.76	86.46	2.3±0.78
	1B	-70.8132	42.7724	1.41	1.38	19.84		3.0 ± 0.61
2	2A	-70.8131	42.7718	1.35	1.36	32.48	307.81	3.2±1.70
	2B	-70.8132	42.7718	1.33	1.36	36.69		3.6
3	3	-70.8128	42.7728	1.16	1.21	5.04	4.20	3.0
4	4	-70.8134	42.7717	1.40	1.40	13.11	63.84	3.1±0.57
5	5	-70.8126	42.7721	1.46	-	66.27*	36.75	2.8
6	6	-70.8125	42.7720	1.43	1.47	69.43*	26.71	1.8
7	7	-70.8127	42.7727	1.37	1.38	9.97	17.94	1.9
8	8	-70.8122	42.7725	1.46	1.46	31.01	7.14	2.8±0.68
9	9	-70.8117	42.7740	1.34	1.37	10.97	5.38	2.7
10	10	-70.8117	42.7732	1.40	1.43	19.34	13.75	4.1 ± 0.60
11	11	-70.8132	42.7722	1.34	1.38	29.93	29.44	3.9 ± 2.23
12	12	-70.8131	42.7722	1.38	1.39	25.22	408.09	2.7
13	13	-70.8131	42.7721	1.37	1.37	46.72	87.97	-
14	14	-70.8128	42.7725	1.36	1.39	28.97	5.47	-
15	15	-70.8127	42.7727	1.38	1.40	19.83	6.58	2.0
16	16	-70.8128	42.7727	1.40	1.41	14.09	8.43	2.3±0.78
17	17	-70.8119	42.7726	1.48	1.50	32.65*	16.38	3.0 ± 0.61

*Patch is close to a pond

Table 2: Sediment analysis results for each patch. Sediment samples were collected in February 2018.

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

Table 3: Summary results of two-way ANOVA model for total number of stems of each species outside and inside over years: stems~position+year+position:year. Position and year are main effects and position:year represents the interaction. Bold text is used to identify significant difference in the levels of each effect. Significance level are set at 10% (α_{crit}=0.1). Df= degrees of freedom; F value and p value are the results of the statistical test, and they need to be compared to F_{crit} and α_{crit}.

Effect		***Position***				
Test		*Df*	*Mean of squares*	*F value*	*F_{crit}*	*p value*
Species	*S.Patens*	1	218870	**10.02**	2.72	**$1.60*10^{-3}$**
	D. Spicata	1	840.74	0.35	0.35	0.57
	S. Alterniflora	1	5454	**13.11**	2.75	**$4.50*10^{-4}$**
	J .Gerardi	1	1.14	$4.00*10^{-4}$	2.74	0.98
Effect		***Year***				

Test		*Df*	*Mean of squares*	*F value*	F_{crit}	*p value*
Species	*S.Patens*	4	238581	**10.92**	1.96	$\mathbf{1.69*10^{-8}}$
	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		***Position:Year***				
Test		*Df*	*Mean of squares*	*F value*	F_{crit}	*p value*
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

Table 4: Summary results of two-way ANOVA model for all heights of each species outside and inside over years: heights~position+year+position:year. Position and year are main effects and position:year represents the interaction. Bold text is used to identify significant difference in the levels of each effect. Significance level are set at 10% (α_{crit}=0.1). Df= degrees of freedom; F value and p value are the results of the statistical test, and they need to be compared to F_{crit} and α_{crit}.

Effect		***Position***				
Test		*Df*	*Mean of squares*	*F value*	F_{crit}	*p value*
Species	*S.Patens*	1	11412	**89.29**	2.72	$\mathbf{<2.20*10^{-16}}$
	D. Spicata	1	688	**7.34**	2.72	$\mathbf{6.77*10^{-3}}$
	S. Alterniflora	1	8674	**50.34**	2.73	$\mathbf{2.18*10^{-12}}$
	J .Gerardi	1	60.9	0.34	2.73	0.56
Effect		***Year***				
Test		*Df*	*Mean of squares*	*F value*	F_{crit}	*p value*
Species	*S.Patens*	4	56500	**442.10**	1.96	$\mathbf{<2.20*10^{-16}}$
	D. Spicata	4	12264	**130.72**	1.96	$\mathbf{<2.20*10^{-16}}$
	S. Alterniflora	4	12139.50	**70.45**	1.98	$\mathbf{<2.20*10^{-16}}$

	J .Gerardi	4	5150.80	**28.82**	1.98	**$<2.20*10^{-16}$**
Effect		***Position:Year***				
Test		*Df*	*Mean of squares*	*F value*	F_{crit}	*p value*
Species	*S.Patens*	4	3185	**24.92**	1.96	**$<2.20*10^{-16}$**
	D. Spicata	4	990.80	**10.56**	1.96	**$1.58*10^{-8}$**
	S. Alterniflora	4	1666.6	9.67	1.98	**$1.06*10^{-7}$**
	J .Gerardi	4	1267.80	7.09	1.98	**$1.24*10^{-5}$**

			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

Table 5: Post-hoc multi-comparison results from two way ANOVA test for stem height inside the patch vs outside.