Hitchhiking halophytes in wrack and sediment-laden ice blocks contribute to tidal marsh development in the Upper Bay of Fundy

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Abstract Salt marshes are a type of coastal wetland that are affected by dynamic coastal processes. Ice blocks and wrack (mats of plant debris) regularly float onto northern marshes and become stranded, affecting vegetation and soil accretion. There is little research regarding the capacity of ice and wrack to transport viable plant propagules onto marshes where they can colonize, which may be particularly important at barren new salt marsh restoration sites. Contributions of sediment by ice may also be important to raise the marsh platform to elevations appropriate for plant colonization. We collected ice ($n = 27$) and wrack ($n = 18$) samples at marshes in the Bay of Fundy, ran germination trials with the contents, and measured the quantity of sediment in the ice. We found viable propagules from halophytic and non-halophytic species in wrack, and viable propagules of *Sporobolus pumilus* in ice. Additionally, we found sediment densities between 0.01 and 4.75 g/cm$^3$ in ice blocks that translated to 26.61–21,483.59 kg of total sediment per block, representing a large source of sediment. We found that the number of germinating propagules could not be predicted by wrack size, and that pH, sediment density, sediment weight in ice blocks were variable across the marsh surface, while ice salinity was negatively correlated with elevation and distance from creek. Our results indicate that ice and wrack represent a potential source for vegetation colonization at salt marsh sites and highlights their contributions to facilitating vegetation colonization through building marsh soils.

Keywords Sediment transfer · Coastal wetlands · Succession · Vegetation dynamics · Restoration

Introduction

Salt marshes are a type of coastal wetland affected by ocean tides, typically found along sheltered shorelines. They occur worldwide, but mainly in middle and high latitudes (Mcowen et al. 2017). A large proportion of salt marsh has been lost globally due to human-engineered barriers to tidal flow, such as dykes, improperly sized or placed tidal crossings (i.e. culverts), and coastal development. Restoration of salt marshes has been occurring with increasing
frequency worldwide as evidence that salt marshes provide beneficial ecosystem services such as protection from storm surge and flooding (Möller et al. 2014), high quality habitat for fish and birds (Hicklin 1987), and climate regulation through carbon sequestration (McLeod et al. 2011) is growing.

Wrack (mats of plant debris; Fig. 1) and ice (Fig. 2) are two common large-scale disturbances in northern salt marshes that can be floated by the tides between and within marshes and influence marsh formation and maintenance. Wrack is typically deposited along the high tide line in spring (Reidenbaugh and Banta 1980) where it can smother vegetation and start secondary succession (Hartman et al. 1983), provide an influx of nutrients (Chapman and Roberts 2004), contribute organic matter to soils where it strands, and deposit viable plant propagules (Minchinton 2006). Ice can also alter marshes by scouring the marsh surface (Dionne 1969; Gordon and Desplanque 1983), removing and depositing sediment, plant propagules, and turfs (Argow et al. 2011; Dionne 1993; Ewanchuk and Bertness 2003), and increasing overall topographic heterogeneity (Dionne 1989; Ewanchuk and Bertness 2003; Pejrup and Andersen 2000). These disturbances have considerable effects on newly restored salt marshes.

Transport of plant propagules by wrack and ice is a function that may play an important role in both mature and developing salt marshes. The effectiveness of vegetation recolonization following salt marsh restoration is affected by the presence of and distance to propagule sources, and propagule dispersal to and within sites (Rand 2000; Wolters et al. 2005). Past research has shown that wrack can transport viable plant propagules from a diverse range of species over distances greater than 2.5 km (Minchinton 2006), and ice has been the suspected source of plant colonization at newly developing salt marshes in the Bay of Fundy where there was no clear source of plant propagules (van Proosdij and Townsend 2006; Virgin et al. 2020). In mature salt marshes, unvegetated areas resulting from disturbances can be colonized by many

Fig. 1 Photograph of a large wrack mat taken at Elderkin on June 5, 2012 by A. Glogowski
species, and succession, especially in high marsh areas, may take a long time to establish typical zonation due to plant dispersal limitations (van Proosdij et al. 2010; Porter et al. 2015). There is little research regarding these modes of dispersal in general, and none in our study area of the Bay of Fundy. Our study sought to confirm the viability of propagules rafting on wrack and ice to better understand the potential for

Fig. 2 Photographs of a piece of composite ice containing multiple blocks melted together and b a flat ice raft taken at the Elderkin marsh in March, 2009 by L. Greene
these dispersal mechanisms to aid colonization at new restoration sites.

The relative elevation of the marsh platform can also influence vegetation recolonization at early restoration sites as subsided elevations can exclude plants from establishing (Garbutt et al. 2006; Rand 2000). As such, contributions of ice laden sediments to soil accretion at these sites raise the marsh platform to an elevation appropriate for plant growth and facilitates vegetation recolonization. Ice is an important contributor to the sedimentary budget in salt marshes in New England, U.S.A., where up to 5% of accreted sediments could be attributable to ice block transport (Argow et al. 2011) and the Saint Lawrence estuary in Québec (Dionne 1989, 1993) where deposits from ice can cover up to 16% of the marsh surface and can weigh as much as $3.0 \times 10^4$ t/km$^2$, and can also alter the effects of waves on coastal erosion (Gibeault et al. 2016). Past research in the Bay of Fundy has also suggested that ice makes important contributions to the sediment budget of marshes in the region (van Proosdij et al. 2006b; Macfarlane et al. 2011; Ollerhead et al. 1999). Salt marsh restoration around the Bay of Fundy addresses the historic loss of coastal wetlands from the region, mainly due to dyking and subsequent conversion to agricultural or other land uses (Bowron et al. 2012). While salt marshes are dynamic systems with frequent disturbances opening up bare areas that are subsequently colonized by plants, restoring tidal flow to formerly dyked systems can result in large bare areas whose vegetation recovery is highly influenced by the availability of plant propagules transported by water or wind, and the availability of sediment to build the marsh surface. The present study compliments this research in documenting the amount of sediment transported by ice onto salt marshes in the Bay of Fundy to provide insight into its potential to facilitate vegetation colonization at new restoration sites.

Methods

Study Region

Ice (one site) and wrack (six sites) sampling occurred in the Minas Basin, an inlet on the Nova Scotia side of the Bay of Fundy in Canada (Fig. 3; Table 1). The Bay of Fundy is a hypertidal estuary with semidiurnal tides that forms the northern extension of the Gulf of Maine. Tidal ranges in the Minas Basin can be higher than in the main Bay and can reach up to 16 m (Desplanque and Mossman 2004). Because of its northern latitude, salt marshes in the Bay of Fundy are also heavily influenced by ice in the winter (Desplanque and Mossman 2004). In the Fundy region, salt marshes are mainly minerogenic due to high suspended sediment concentrations (van Proosdij et al. 2006a). They are typically stratified into two main vegetation zones, the low marsh dominated almost entirely by $Sporobolus alterniflorus$ (Loisel.) (formerly $Spartina alterniflora$), and a wider high marsh zone that can be dominated by a range of species depending on local salinity and flooding conditions (Pratolongo et al. 2019).

Ice propagule and sediment transport

Sampling

The Elderkin marsh was stratified into three zones [high marsh (16.7 ha), low marsh (10.4 ha), mudflats (12.6 ha)] based upon site hydrology and the presence of vegetation. Zones were delineated in ArcGIS 9.3 using a digital elevation model (DEM) referenced to Canadian Geodetic Vertical Datum 1928 (CGVD28; created from LiDAR and IKONOS satellite imagery from 2007) and aerial imagery (IKONOS satellite imagery) as follows: the high marsh zone was identified as areas with elevations between 7.57 m (Higher High Water Large Tide) and 5.77 m (Higher High Water Mean Tide), the low marsh zone was the area between 5.77 m elevation and the edge of vegetation, and the mudflat zone was the area between the edge of vegetation and the lower elevation bound of $-0.03$ m (Mean Water Level) (Fig. 4). Fifteen random points were identified in each zone as target locations for sampling ice blocks.

Sampling occurred on March 17, 21, and 27 2009, during spring tides. The nearest ice block within ~20 m of each target location was sampled. Coordinates, length, width, and height of each block were recorded with care taken to measure the central mass of ice (attempting to measure the mean extent of the block, ignoring overhangs or other protrusions or hollows), and a photograph was taken. Ice blocks were broken apart using an axe to determine whether rhizomes or dead plant material were present. Two
samples were taken from the ice block using a serrated knife, one from the edge of the block and one from the interior. If rhizomes were present, one of the samples was taken from that area of the block. Both samples were placed in the same plastic bag and stored in a cooler.

**Lab analyses and germination trials**

Ice samples were melted at room temperature and rhizomes were removed, rinsed of sediment and stored in plastic bags in a refrigerator at 4 °C for 2 months. Melted ice was pipetted into graduated cylinders, leaving settled sediment, to measure volume. The initial volume of ice was estimated by converting the melted volume to ice volume with a ratio obtained by measuring a bag of ice cubes’ volume using water displacement, and the volume of the melted cubes. Water was then tested for pH, salinity and conductivity using a YSI probe (model 600QS-0-0).

Sediment was left to dry and then weighed. It was then wet sieved using a 0.063 µm and 0.125 µm sieve to separate organic (seeds) and inorganic material. Suction filtration was performed on water samples and water from rinsed rhizomes, then filter papers dried at 105 °C for 2 h, cooled in a dessicator overnight and weighed to obtain additional sediment weights, which were added together for a total weight. The sediment slurry was retained for germination trials.

Total sediment weight in the ice blocks was calculated using sediment density in the samples and multiplying by the ice block volume (calculated by multiplying the measured dimensions of the block).
Sediment density data were also compared to the sediment density of a neutrally buoyant ice block calculated using the formula:

\[
C = \frac{(\rho_w - \rho_i)}{(1 - \frac{\rho_i}{\rho_s})} = 0.163 \text{ g/cm}^3
\]

where \( C \) sediment density, \( \rho_w \) the density of sea water at 5 °C (1.0 g/cm³ with salinity of 29.5 ppt), \( \rho_i \) the density of ice (0.9167 g/cm³), and \( \rho_s \) inorganic particle density for mean grain size of 23–30 µm (2.65 g/cm³) to determine whether blocks were positively or negatively buoyant and therefore understand whether they were likely to be refloated after stranding on the marsh surface.

The sediment slurry was sown onto sand in trays and kept in a greenhouse (16:8 h light/dark cycle and 25:18 °C day/night temperature). Trays were watered and number of shoots was counted daily for 1 week and then every other day for 8 weeks.

**Post-processing and statistical analysis**

ArcMap 9.3 was used to extract the elevation at which blocks were found from the DEM. Creek thalwegs were digitized from aerial imagery and Spatial Analyst tools were used to automatically measure the distance from each block to the thalweg of the nearest creek. To determine whether the three marsh zones differed in ice and sediment characteristics, one-way anovas (with gaussian distribution) were assessed in R 3.6.0 (R Core Team 2019) with transformations to improve residual distributions using the following

| Site       | Site code | Sample type | Lat (°N)   | Long (°E)   | Site size (ha) | Dominant vegetation                                      | Notes                                                                 |
|------------|-----------|-------------|------------|-------------|----------------|----------------------------------------------------------|----------------------------------------------------------------------|
| Cogmagun   | Cog       | Wrack       | 45.077889  | − 64.131917 | 350            | *Sporobolus pumilus, Carex paleacea* (Limonium carolinianum and Solidago sempervirens also present) | Small marsh within large tidal river                                  |
| Elderkin   | Eld       | Wrack + Ice | 45.003051  | − 64.151929 | 40             | *Sporobolus alterniflorus, Sporobolus pumilus*           | Young marsh formed after construction of Windsor causeway in 1970 (van Proosdij and Townsend, 2006). At river mouth |
| Kingsport  | Kp        | Wrack       | 45.141889  | − 64.398556 | 200            | *Carex paleacea, Scirpus americanus*                     | Historically dyked salt marsh that was naturally restoring for the past century. Large coastal marsh |
| Lantz      | Ltz       | Wrack       | 45.173222  | − 64.157778 | 50             | *Carex paleacea*                                        | Previously tidally restricted marsh, restoring spontaneously after failure of culvert and causeway ~ 10 years prior to sampling; small marsh in tidal river |
| Noel       | Nl        | Wrack       | 45.299278  | − 63.729528 | 200            | *Sporobolus pumilus, Carex paleacea* and Solidago sempervirens | Large coastal marsh                                                                 |
| Walton     | Wal       | Wrack       | 45.221361  | − 63.996444 | 350            | *Sporobolus alterniflorus, Sporobolus pumilus* (Carex paleacea also present) | Small marsh within large tidal river                                  |
Fig. 4 Delineated zones of the Elderkin marsh with locations of ice blocks sampled in March 2009 indicating which blocks contained rhizomes.
variables: ice block volume, sediment density (ln(x) transformed) and weight (ln(x) transformed), distance to creek (ln(x) transformed), pH and salinity (ln(x) transformed) in blocks. To determine whether elevation or distance to creek could predict the above variables, we used ordinary least squares regression using elevation and distance to creek (ln(x) transformed) as predictors.

Wrack propagule transport

Field

Field sampling was conducted at salt marshes in Noel, Cogmagun, Walton and Lantz on June 1, 2012 and Elderkin and Kingsport on June 5, 2012. Each sampling day, recent and current tide cycles and the weather were noted. One wrack mat (>10 m long and >1 m wide; Fig. 1) was located in the center, and at either end of the marsh running parallel to the water (n = 18; Figures R1–R6). A 1 m² quadrat was blind tossed onto the mat and wrack depth was measured at 5 locations in a line (at the center of the quadrat, each side of the quadrat, and 5 m to either side of the quadrat). All wrack material inside the quadrat was collected into a garbage bag. Dominant species in the extant vegetation around the wrack mat was noted.

Lab analyses and germination trials

Each sample was weighed (wet weight) and visually divided into quarters. One quarter was dried at 80 °C for 48 h then weighed (dry weight). Two quarters were wet sieved using a 5 mm and 0.2 mm sieve. Seeds retained in the 0.2 mm sieve were sewn onto sand in trays, covered with ~2 mm of sand and kept in a greenhouse (16:8 h light/dark cycle and 25:18 °C day/night temperature). Past studies on halophytes have shown they germinate better in fresh than salt water or show no differences in generation rate (Heim et al. 2018). Trays were watered with tap water once daily for 15 weeks then identified and counted. General linear models with negative binomial distribution were fitted in R 3.6.0 (R Core Team 2019) using wet weight, dry weight, and wrack depth as predictors for the total number of germinated seeds per sample; the number of germinated seeds was ln(x + 1) transformed to improve homogeneity of variance and reduce in the influence of two outlier samples with very high seedling densities (Table R2).

Results

Ice propagule and sediment transport

Ice blocks were found at 27 of 45 pre-determined sample points. Ice previously covered the entire site (e.g. in January) but ice coverage at the time of sampling in March was approximately 60%. Ice blocks on the marsh were various shapes and sizes, some consisting of multiple pieces melted together (composite ice; Fig. 2a), while others were flat with a thickness of <1 m (Fig. 2b). There was a thin layer of snow on some blocks while others were melting and covered in sediment which was slumping off onto the marsh surface. The distribution and density of blocks across the marsh surface varied over the three sampling days, with an observed decrease in the number of blocks on the marsh over time, potentially indicative of the timing in the tide cycle. Ice blocks on the mudflats were all found in tidal creeks. Flat ice was mainly found in high marsh (<0.6 m thickness) (Fig. 4). Larger ice blocks were found in the low marsh and mudflats (>0.6 m thickness) (Fig. 4), with the largest blocks found in the low marsh (Table 2; Fig. 4).

Salinity was greater in the mudflats than low and high marsh (Table 2) but blocks did not differ significantly in estimated volume, sediment density distance to creek or pH; salinity was negatively correlated with elevation and distance from creek, but sediment density and weight, ice pH, and ice block estimated volume were not correlated with either potential predictor. Generally, two types of dominant sediment were observed in the ice: sandy mud with occasional shells, and rich organic mud containing S. alterniflorus rhizomes characterized by a layer of black anaerobic sediment, indicating different sources of sediment. Seventeen of the 27 ice blocks were negatively buoyant.

Of the 27 ice blocks, 9 contained rhizomes or marsh turf and 6 contained dead plant material. These blocks were found in all zones of the marsh (Fig. 4). The dead plant material appeared to be mainly S. alterniflorus stems that had broken off at the base. Collected ice samples contained Sporobolus pumilus (Roth) P.M. Peterson & Saarela (formerly Spartina
patens) and *S. alterniflorus* rhizomes. Twenty-three *S. pumilus* shoots sprouted within 5 days in the greenhouse and two more shoots were observed after 8 weeks. Viable rhizomes were from two ice block samples, both found in the high marsh. No seeds germinated from the sediment slurries.

**Wrack characteristics and seed germination**

All sites contained at least some large wrack mats (Table R1) ranging up to 30 m across and over 300 m long, and covering more than 1 ha in total (e.g. more than 2% of the total marsh area at Elderkin), found almost entirely in the high marsh. Depth of wrack in the field ranged from 3 to 13 cm (average 7 ± 1 cm) (Table R1). The majority of plant debris that made up the wrack was identifiable as *S. alterniflorus* or *Juncus gerardii*. Seeds germinated from all samples (Table 3). There were no significant relationships between dry weight or depth of wrack and the number of germinating seeds in the samples. Overall, ten plant species grew enough to maturity to be identified and there were 1410 individuals germinating in total (Table 3; Fig. 5). Many *Juncus* seeds germinated but few germinated from identifiable inflorescences that could be attributed to *J. gerardii*. Cyperaceae were the most frequent taxa germinated (Fig. 5); these were likely bulrushes (*Scirpus, Schoenoplectus, Bolboschoenus*) or sedges (*Carex paleacea*, found in the extant vegetation at most sites) based on seedling morphology. Of seedlings we could identify to species, halophytic species such as *J. gerardii, Solidago sempervirens* and *Plantago maritima* were the most frequent and abundant, with a handful of weedy species and one tree seedling making up the rest (Fig. 5; Table 3). Similarly, the seedlings identified as *Juncus* spp. were likely *J. gerardii* as this is the most common species in the area that would be affected by

### Table 2 Summary statistics for various ice block characteristics

| Zone      | Ice block volume (m$^3$) | Sediment density (g/cm$^3$) | Total sediment (kg) | Elevation (m) | Distance to creek (m) | pH  | Salinity (ppt) | Sample size |
|-----------|--------------------------|-----------------------------|----------------------|---------------|----------------------|-----|----------------|-------------|
|           | Mean SD                  | Mean SD                     | Mean SD              | Mean SD       | Mean SD              | Mean SD | Mean SD       | Mean SD     |
| High marsh| 6.74 5.98                | 0.32 0.51                   | 2500.79 4938.85      | 6.26 0.39     | 45.86 39.00          | 7.83 | 0.18          | 0.41a 0.22 | 5           |
| Low marsh | 14.77 11.29              | 0.35 0.43                   | 4916.29 5644.19      | 5.28 0.44     | 34.19 20.15          | 7.87 | 0.23          | 1.06a 0.66 | 16          |
| Mudflats  | 9.62 9.80                | 1.13 1.79                   | 4812.97 7442.20      | 4.34 2.01     | 29.05 40.34          | 7.75 | 0.22          | 2.53b 1.33 | 6           |

Elevation was measured relative to CGVD28. Salinity and pH were measured using one less sample as melted samples did not have a large enough volume to test. Means with different subscript letters are considered significantly different at $\alpha = 0.05$

### Table 3 Halophytic status of species that germinated from wrack germination trials and corresponding sites from which they germinated

| Species                             | Site (codes from Table 1) | Type          |
|-------------------------------------|---------------------------|---------------|
| *Cerastium fontanum* Bauum          | Ltz                       | Non-halophytic|
| Cyperaceae (*Carex or Scirpus/Schoenoplectus/Bolboschoenus*) | Eld, Cog, Kp, Ltz, Ni, Wal | Probably halophytic |
| *Juncus gerardii* Loisel            | Ni                        | Halophytic    |
| *Juncus* sp.                        | Cog, Kp, Lz, Ni           | Probably halophytic |
| *Picea glauca* (Moench) Voss        | Ni, Wal                   | Non-halophytic|
| *Plantago maritima* L.              | Cog, Ltz, Wal             | Halophytic    |
| *Poa compressa* L.                  | Eld                       | Non-halophytic|
| *Solidago sempervirens* L.          | Cog, Kp, Ltz, Ni          | Halophytic    |
| *Sonchus* sp.                       | Ni                        | Non-halophytic|
| *Stellaria* sp.                     | Ni                        | Non-halophytic|
| Unknown Species A                    | Ni                        | Unknown       |
| Unknown Species B                    | Wal                       | Unknown       |
tidal flooding and dead material identified to that species was common in the wrack. Assuming that *Juncus* sp. are *J. gerardii*, all three identified halophytes occurred at three or more sites (Table 3).

**Discussion**

Our results indicate that plant propagules transported by wrack and ice in the Bay of Fundy are viable and have the potential to colonize salt marsh sites. Viable propagules from 12 species were found in wrack across all six study sites. Plant propagules were also found in 9 of 27 ice samples, and those in two blocks were viable. In addition, we confirmed that ice can carry large amounts of sediment and has the potential to contribute significantly to marsh accretion and therefore vegetation colonization at new restoration sites or other early successional salt marshes. While ice did carry some viable rhizomes, less than 10% of sampled blocks had these, so the importance of ice to marsh development and vegetation dynamics may be more via sediment deposition than transport of live plants.

Prolific seed producers tended to be best represented in germinating specimens from the wrack. These included perennials (both halophytic and non-halophytic) such as *J. gerardii*, *Plantago maritima* and *Solidago sempervirens* but also early season annuals such as *Sonchus* sp., *Stellaria* sp., and *Cerasium fontanum*. Assuming that the majority of *Juncus* seedlings were *J. gerardii*, halophytic species were most abundant, mirroring communities found in salt marshes in the area (Porter et al. 2015). Wrack can form from the current season’s growth or the previous season’s growth, and the two forms are generally distinguishable (Reidenbaugh and Banta 1980). Since wrack was collected in the spring in our study, it is likely that all seeds were from the previous growing season. An interesting avenue for future research would be to investigate whether seeds and rhizomes deposited by wrack are produced in the current or past growing season, how this changes over the course of the season, and how this process relates to plants’ dormancy requirements.

There was a distinct lack of *Sporobolus* spp. germinating from wrack samples, although their rhizomes did appear to be present. These are typically the dominant species in salt marshes in the study region (Porter et al. 2015) and *S. alterniflorus* is an ecosystem engineer frequently colonizing new restoration sites (Bruno 2000; van Proosdij et al. 2010). *S. alterniflorus* may colonize bare surfaces of salt marshes largely via seeds transported in the fall at maturity via water, prior to the breaking off of stems and leaves to form wrack and the formation of ice in winter. It is interesting that these species were not represented in the wrack since *S. alterniflorus’ long-range dispersal

![Fig. 5](image-url) Germinated seeds from wrack collected from six sites in Bay of Fundy tidal marshes. Frequency indicates the number of samples the taxon was identified in (out of 18). The number above the bar indicates the total number of individual seeds germinated for each taxon. “Unk” refers to two taxa that could not be identified.
is thought to be facilitated through seed rafting on wrack (Davis et al. 2004), and S. pumilus is likely to do the same because of their similar morphologies. It is possible that Sporobolus spp. were absent from the wrack because the previous season’s seeds may have shattered and been dispersed in some other way as they do not grow in seed capsules. It is also possible that seeds were present but not viable, or that larger rhizomes of these species were sieved out in our study, removing them from our germination trials. Propagules of Sporobolus spp. were, however, found in ice blocks, and S. pumilus propagules were confirmed to be viable, demonstrating ice as a potential source for these species at new restoration sites or early successional natural marshes. Though we did not find viable Sporobolus spp. in wrack or viable S. alterniflorus in ice, it is highly likely that they can be transported in this way (Davis et al. 2004; Minchinton 2006; van Proosdij and Townsend 2006) and more extensive testing would provide better information on the importance of these dispersal mechanisms for these specific species. The other species detected as viable seeds in the wrack (Fig. 5) likely travel in water as individual seeds or via wind (e.g., in Solidago sempervirens) as well, and for the most part do not make up the dominant vegetation in salt marshes. This study shows that wrack, at least, can transport these propagules to appropriate sites to germinate (wrack was found in the high marsh zone and these species are typically found growing in the highest elevations of salt marshes (Porter et al. 2015)). Juncus gerardii can make up the dominant vegetation in higher elevation high marsh zones and wrack may represent an important dispersal mechanism for this species.

Physical characteristics (e.g., depth, size) of wrack mats were not predictive of the amount of germinating seeds and were highly variable among sites. Similarly, the presence of rhizomes in ice blocks was not predicted by their location on the marsh, or their size (volume, thickness). Environmental and geographical factors such as the weather, tides, season, marsh topography, and distance to neighbouring marshes could affect the physical characteristics, contents and stranding location of wrack and ice, making them somewhat unpredictable sources of plants in salt marshes and therefore difficult to harness for restoration. In addition, ice blocks are in many cases a composite of multiple freezing and stranding events at different elevations within a marsh depending on the tides, with layers of sediment and rhizome material being incorporated into the ice block matrix (Argow et al. 2011; Fig. 2a). Exploring how these characteristics affect the ability of wrack and ice to transport plant propagules would increase understanding of these forces in restoration projects.

In addition to directly transporting viable plant propagules, we found that ice blocks can carry and contribute large amounts of sediment to marshes, which contributes to raising the elevations in developing marshes to levels at which inundation times are decreased enough to allow plant growth. A sediment study adjacent to Elderkin Marsh gives an estimate of 7.8 ± 13 mg/cm² of deposition from water per flood tide (Daborn et al. 2003) which would result in a total of 275 tonnes/ha for one year for sediments transported in tidal water. Estimates of ice-transported sediment in the Upper St. Lawrence Estuary were estimated by Dionne (1993) to be 300–350 tonnes/ha. Assuming 60% of coverage of Elderkin Marsh by ice blocks with the same characteristics of our samples and that these would all melt in place we can estimate 1800 tonnes/ha of sediment would be deposited from melting ice blocks. It must be pointed out that both water borne and ice borne sediment deposition is highly spatially and temporally variable, so these estimates have a great amount of associated uncertainty. This process of sediment deposition by melting ice blocks might also aid in allowing salt marshes to accrete sediment and keep pace with sea level rise. This agrees with past research finding that ice contributes considerably to the sediment budget at salt marshes (Argow et al. 2011; Gordon and Desplanque 1983; Ollerhead et al. 1999; Pejrup and Andersen 2000; van Proosdij et al. 2006b). There was large variability in sediment densities and total sediment weights in our ice, which may be reflective of the wide range of mechanisms through which sediment can be accumulated (e.g., deposited through settling and freezing, ice blocks freezing to the ground and ripping out marsh surface, and directly from the water where suspended sediment concentrations are high; Argow et al. 2011). We found no relationship between amounts of sediment and distance from creek or zone, indicating that large blocks with high sediment concentrations may be present anywhere on the marsh surface. These findings are in opposition to past research finding that sediment concentration in ice decreased logarithmically with distance.
from creek (Argow et al. 2011). This discrepancy is likely a result of the season in which ice blocks were sampled; while Agrow et al. (2011) carried out their research in the winter, we sampled nearer to spring, when temperatures were higher and many ice blocks were observed melting, effectively increasing sediment concentrations. Sediment concentrations may have also been affected by the large tidal range in the Bay of Fundy allowing heavier blocks to travel farther from creeks, or relative inundation times at blocks’ stranding locations, where longer periods allowed more sediment to settle and freeze to the blocks. Though we have confirmed that ice can contribute to the sediment budget at Fundy salt marsh restoration sites, there are still some unknown factors controlling the amount of sediment that can be transported onto the marsh, and where it can be deposited.

There is conflicting information regarding the degree to which ice can travel between marshes. It has been hypothesized that once ice blocks are grounded on a marsh, they can move farther onto the marsh but are not typically removed (Pejrup and Andersen 2000; Reidenbaugh and Banta 1980); however, in Bay of Fundy systems this is not the case. Sanderson and Redden (2015) report observations of Sporobolus-containing ice blocks discovered over 1 km from existing salt marsh vegetation in the Minas Basin. In our study we observed movement and removal of ice blocks over the course of the sample period, indicating that the macrotidal Fundy tides can rapidly change the icescape on salt marshes. However, we found that the majority of sampled ice blocks were negatively buoyant and unlikely to be refloated by the tide. Since our sample period was near the end of the winter, many of the blocks were experiencing obvious melting, which concentrated sediments and decreased the buoyancy of the blocks.

Climate change is likely already affecting the movement of ice and wrack in Bay of Fundy tidal marshes. To form, ice needs several consecutive days with air temperatures below zero during neap tides. Ice first freezes in creeks and can be transported elsewhere during spring tides. Predicted number of days below freezing in the Cumberland Basin (Bay of Fundy) by 2030 declines to 138 days (range 119–156) from the 2004 historical mean of 148 days (range 137–169) in the RCP 8.5 climate scenario (Environment and Climate Change Canada 2021). Warmer winters may decrease the availability of ice to Fundy salt marshes but could also result in greater movement of wrack and ice blocks among sites because there is likely to be less of the ice season where the entire surface of a marsh is covered and protected by a stable layer of ice. However, it must be emphasized that in Atlantic Canada warming has been driven by summer rather than winter temperature increases (Dietz and Arnold 2021).

Additionally, most salt marsh restoration initiatives in the region focus on restoring tidal hydrology and fish passage (Bowron et al. 2012); while the ability of ice to enter previously restored marshes and whether future design can facilitate ice movement has been considered (e.g. wider breach openings), it has not been quantified. Further research is needed to determine how far blocks can travel in Fundy systems and the influence of factors such as winter weather, currents, topology of tidal access to wetlands such as breach dimensions and position within the estuary, and timing of the season on ice block transit.

**Conclusion**

Wrack and ice are both mechanisms through which viable plant material of a range of species can be deposited at new and natural salt marsh sites. These are both, however, highly unpredictable sources of plant material that can be affected by seasons, tides, and weather, among other factors. Wrack and ice may be important long-range transport mechanisms of plant propagules in Fundy systems, and they may be uniquely influenced by the conditions in the Bay of Fundy. Wrack and ice also contribute to the development of restored marsh soils which facilitates the subsequent colonization by vegetation. There are many opportunities for future research regarding these modes of plant dispersal in the Bay of Fundy which will lead to an improved understanding of ideal restoration designs and successional trajectories in the future.

**Acknowledgements** This research was supported by National Sciences and Engineering Research Council (Canada) Discovery grants to D. van Proosdij and J. Lundholm.

**Author contributions** All data generated or analysed during this study are included in this published article [and its supplementary information files]. Study conception and design were carried out by LG, ADG, TB, DP and JTL. Material
preparation, data collection and analysis were performed by LG, ADG, TB, DP and JTL. The first draft of the manuscript was written by TRMR. All authors read and approved the final manuscript. All data generated or analysed during this study are included in this published article [and its supplementary information files].

**Funding** This research was supported by National Sciences and Engineering Research Council (Canada) Discovery Grants to D. van Proosdij and J. Lundholm.

**Declarations**

**Competing interest** The authors have not disclosed any competing interests.

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