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Spatial and Temporal Patterns of Salt Marsh Colonization Following Causeway Construction in the Bay of Fundy

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ABSTRACT

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Construction of causeways across tidal estuaries causes significant change to the coastal system and salt marshes are the first environments to feel these effects. This paper presents results from a field study and GIS analysis on quantifying the spatial evolution and rate of growth of *Spartina alterniflora* and current rates of sediment accretion on a macro tidal salt marsh /mud flat system since causeway construction across the Avon River estuary in 1970. The boundaries of *Spartina alterniflora* colonies were measured in the field at low tide using differential GPS in the Fall of 2001. The historic spatial distribution of salt marsh vegetation was determined from aerial photographs from 1973, 1981, 1992 and 1995. The annual rate of growth and change in salt marsh area from 1969 to 2001 were quantified and analyzed using GIS. Detailed measurements of sediment and vegetation characteristics and sediment accretion were all measured during the 2002 summer season The rate of growth of the area of marsh vegetation has been increasing at an exponential rate since causeway construction due to high rates of sediment deposition and consolidation as well as ice rafting of rhizome material. The rate of growth increased markedly from 11% to 37% per annum after 1992 once the vegetation was firmly established. The construction of the Windsor Causeway altered sedimentation patterns in the region and, coupled with ice rafting of rhizome material and high rates of sediment accretion, lead to the evolution of a rapidly expanding, highly productive salt marsh system.

ADDITIONAL INDEX WORDS: *Sediment accretion, ice rafting, GIS.*

INTRODUCTION

Construction of causeways across tidal rivers and estuaries causes significant change to the geomorphology and ecology of the coastal system and salt marshes are the first environments to feel the effect of coastal modification (DABORN, 1987; MILLER *et al*., 2001). The Windsor Causeway in the Minas Basin of the Bay of Fundy is no exception. Barriers decrease turbulent energy in the tidal system causing sediments and other particles to drop from suspension and accumulate as deposits of mud, sand and silt (WELLS, 1999). Since its closure in June 1970, a salt marsh / mud flat system has accumulated on its seaward side (Figure 1), whose characteristics have visibly changed during the last three decades as it became colonized by *Spartina alterniflora*.

Preliminary research by AMOS (1977, AMOS and JOICE, 1977) suggested that sediment was accumulating at distances up to 20 km seaward of the causeway, as a result of the decrease in tidal prism. Direct measurements were made of the rate of sediment accretion on the Windsor mudflats during 1975 and 1976: rates ranging from 1.0 to > 14 cm·mth^{-1} were calculated. The rapid rate of settlement produced a soft, muddy deposit that

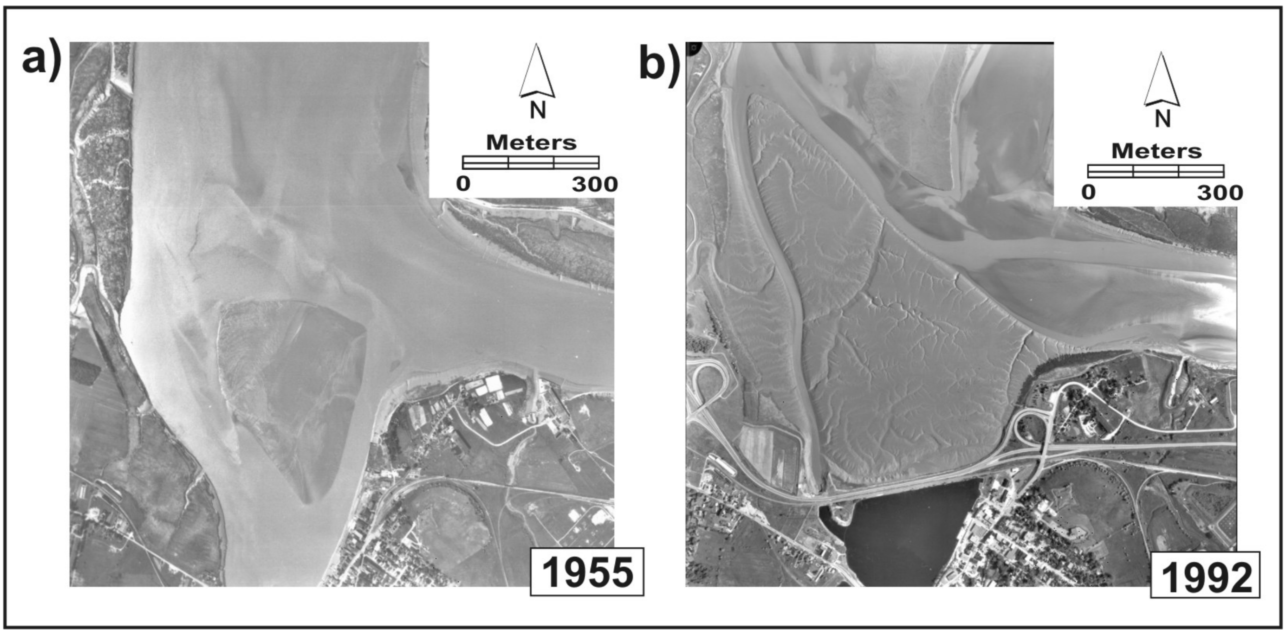

Figure 1. a) Avon River and Town of Windsor in 1955 at low tide before causeway construction and in b) 1992, after causeway construction and significant amounts of sediment had accumulated seaward of the barrier.

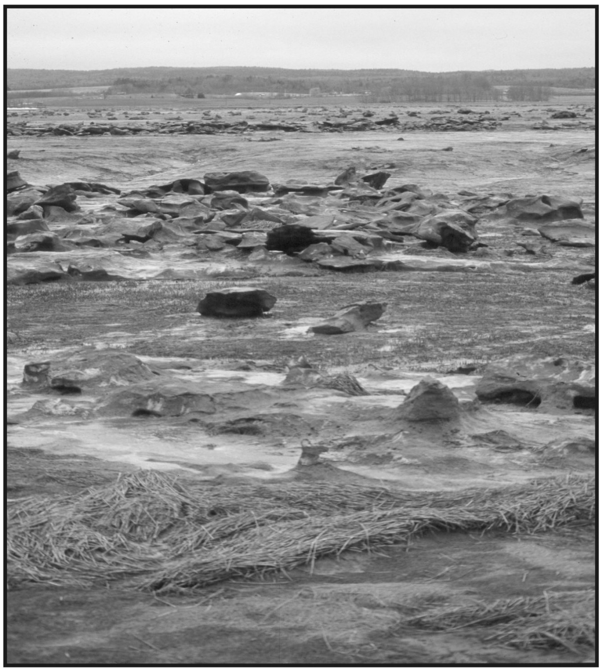

Figure 2. Ice cakes seaward of the Windsor causeway in December, with dead *S. alterniflora* stems in the foreground (TOWNSEND, 2002).

remained very fluid. Over time this material consolidated and residents in the area began noticing discrete patches of salt marsh vegetation growing seaward of the causeway. Over the last few years, this once barren mudflat has been transformed into a lush, saltmarsh ecosystem visited by a wide range of waterfowl and migratory shorebirds. Concern has been raised regarding plans to twin the highway and the impact on the surrounding coastal environment.

The purpose of this study was to determine the spatial and temporal patterns of salt marsh colonization after causeway construction and to quantify the rate of change in vegetation area. *Spartina alterniflora* is the dominant colonizer of the low marsh in the Bay of Fundy, adapted to thrive in the harsh intertidal environment. Growth occurs generally from late spring to mid fall after which the above ground vegetation dies and is broken off during the winter by ice formation (Figure 2) and tides. The rhizomes and roots however survive the winter in the mud and push up new growth each spring (GALLAGHER *et al.*, 1983). *S. alterniflora* can spread by seed or rhizome which are both buoyant, or by vegetative fragmentation (DAEHLER and STRONG, 1994). In temperate latitudes, approximately 40% of rhizome growth occurs in the upper 5 cm of soil from April to

Figure 3. Established *Spartina alterniflora* ring formation colony with established satellites in the background in July 2001.

October (SMART, 1982). Rhizomes form an extensive root system that is roughly five times larger than its aboveground biomass supporting colonization of uninhabited mudfalts at a rapid rate through rhizome outgrowth (REDFIELD, 1971).

Once established, *S. alterniflora* spreads forming "ring-shaped clumps of individual clones or satellites" (TYLER and ZIEMAN, 1999). These clones are often tall and conspicuous against open mudflats (Figure 3). New stems grow along the outer edge of the ring, gradually increasing its diameter each year, while old, dying vegetation can be found in the middle (DAEHLER and STRONG, 1994). As clones spread, they grow into each other, forming a dense monospecific new salt marsh.

METHODS

The Bay of Fundy is a macro-tidal estuary characterized by a semi-diurnal tidal regime with a tidal range of at least 12 m, high suspended sediment concentrations and the presence of ice and snow for at least three months of the year. During this period, much of the marsh vegetation is either sheared off, exposing base sediment or buried under snow and ice. The research was conducted on a section of the Avon River estuary in the Minas Basin near the town of Windsor, Nova Scotia, Canada (Figure 4).

The extent of both 'established' and 'juvenile' colonies of *Spartina alterniflora* were surveyed in the field at low tide using a Trimble Pro XR Global Positioning System (GPS) using a set base station and carrier phase mode in the Fall of 2001. The horizontal and vertical accuracy (at the 95% confidence level) of the surveys ranged from 0.1 to 1.2 m. The lower accuracy resulted from the spatial variability in the strength of the mudflat surface which made surveying difficult. An 'established' colony was identified as a vegetated area measuring over 2m^2, containing mature *S. alterniflora*, possessing flowers or seedpods (TOWNSEND, 2002). Juvenile colonies were identified as *S. alterniflora* lacking flowers or seedpods, between areas of established vegetation and non-vegetated mud surfaces, with a distribution density of more than 10 shoots per m^2 (TOWNSEND, 2002).

The historic spatial distribution covered by salt marsh vegetation was determined from aerial photographs of the study area from 1973, 1981, 1992 and 1995. No vegetation was present prior to 1973. Aerial photographs were scanned at the appropriate resolution and vegetation outlined using on-screen digitizing in ArcView 3.2 (ESRI: Redlands, CA) with Image

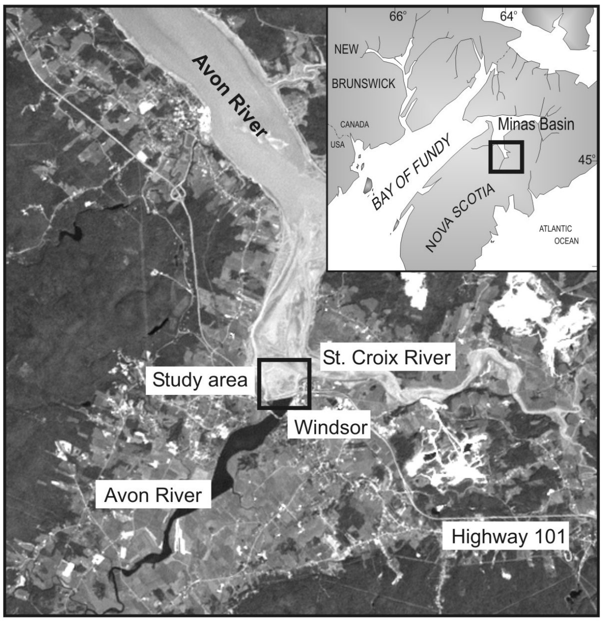

Figure 4. Satellite image depicting the location of the study area in the Avon River estuary of the Minas Basin near Windsor, Nova Scotia.

and Spatial Analyst extensions with various additional avenue scripts. The GPS line surveys were also converted to polygons within the GIS program. The annual rate of growth and change in total marsh area from causeway construction in 1970 to 2001 were quantified and analyzed.

Detailed sampling of sediment (for grain size, organic matter content and bulk density) and vegetation characteristics (species richness, height and density) was undertaken at 47 stations arranged along 10 transects during the 2002 summer season. Ten cm core samples were analyzed for grain size using a Coulter Laser 2000 system and organic matter content was determined from loss on ignition. Sediment accretion was measured at 33 sampling stations from buried aluminium plates at 2-week intervals over the course of the summer and monthly during the fall. Spatial variability in suspended sediment concentrations were measured using 12 rising stage bottle samplers over four successive tides in July 2002. These data were collected as part of a concurrent, on-going sediment dynamics study in the area.

RESULTS AND ANALYSIS

The marsh/ mudflat surface consists primarily of clayey silts with water contents ranging from 30 to 57% and contain between 0-17% organic matter (DABORN *et al*., 2003). Short-term monitoring indicates that the majority of the marsh surface has increased in elevation by 0.3 (± 0.4) cm·mth^{-1}. Decreases in elevation were recorded in areas adjacent to tidal channels where there was visible evidence of slumping and erosion. The ambient sediment concentrations in floodwater over the marsh ranged from high values of ~ 500 mg·l^{-1} at the edges of the marsh to less than 100 mg·l^{-1} at stations in the middle of the marsh.

Initial marsh growth was found adjacent to the dyke near the Tourist Bureau in 1973 (Figure 5a) and subsequently (1981) at the western end of the causeway (Figure 5b). The first detectable marsh on the mudflat was recorded as an isolated patch in 1981 (Figure 5b) in the northeast portion of the mudflat; it was presumably rafted in by ice. By 1992, there were more than 30 such isolated patches (Figure 5c), probably representing several ice-rafted events as evidenced by the presence of cobbles and a 0.5 m boulder near some of these colonies. These isolated groups coalesced as *Spartina alterniflora* spread by rhizome expansion. However, between 1992 and 1995, approximately 30 m of mudflat erosion was recorded at the junction between the St. Croix and the Avon River. By 1995, an additional 26,550 m^2 of *S. alterniflora* had become established (Figure 5d). Between 1995 and 2001 (Figure 5e), the marsh grew from ~41,000 m^2 to > 390,000 m^2. At the same time however, approximately 105 m of mudflat erosion was recorded along the NE edge and a number of established vegetation satellite communities were lost in this region.

The overall rate of growth of *S. alterniflora (S. alt.)* over the 32-year period is 15% however, closer examination of the data suggest that the rate of growth increased markedly around 1992. An exponential curve was therefore fitted to the pre and post 1992 data creating two rates of growth (Figure 6).

From 1969 to 1992, the area of *Spartina alterniflora* increased at a rate of 11%. After 1992, the rate of growth tripled to 37% or at the very least doubled to 29% if only the established vegetation were used in the calculation. Since the juvenile vegetation could not be distinguished from established vegetation when interpreting the aerial photographs, the rate of 37% will be accepted as the final rate of growth. Baring a significant environmental event and no modification to the existing causeway structure, the exponential growth of *Spartina alterniflora* (37%) will result in it covering almost all of the Windsor tidal flats by 2005.

DISCUSSIONS

From the spatial analysis of aerial photographs and GPS field data, and growth models of *S. alterniflora,* it is possible to

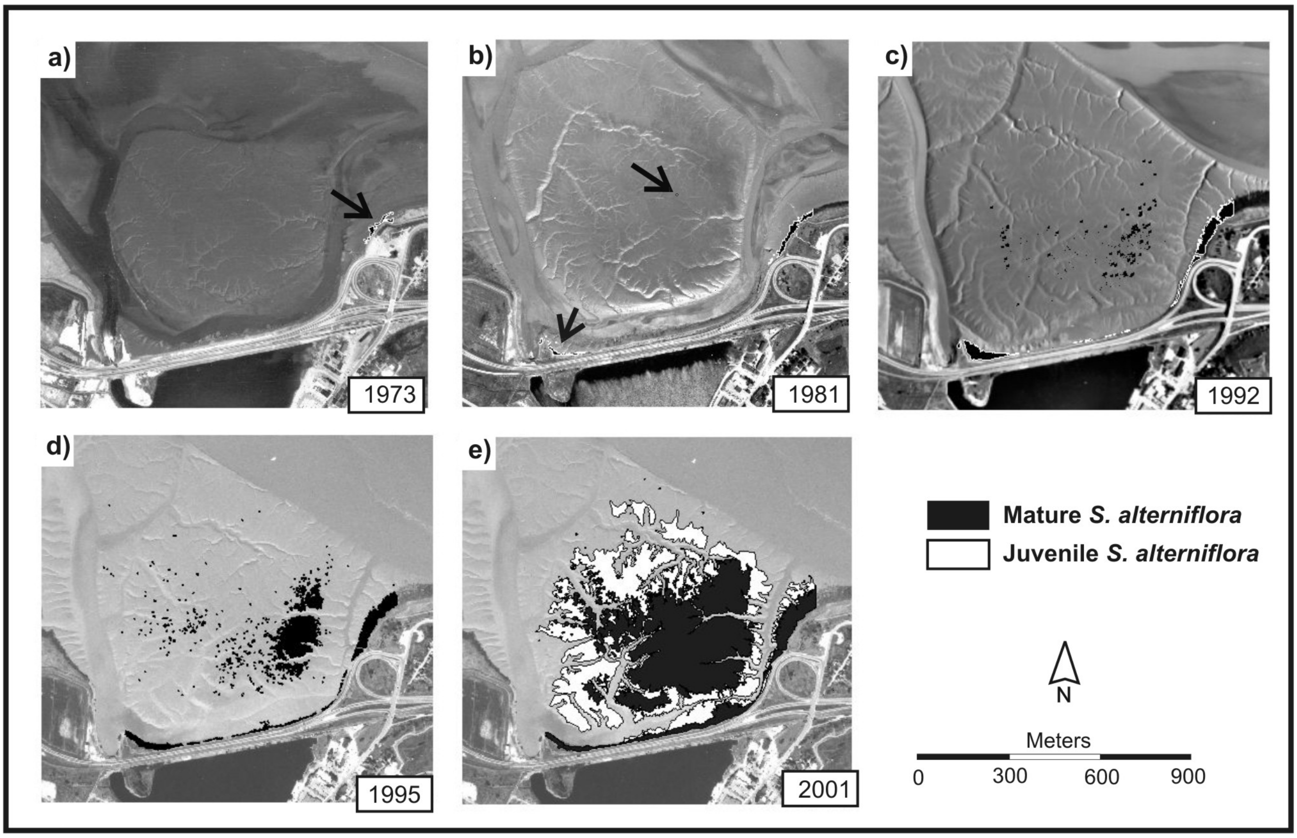

Figure 5. GIS analysis of spatial patterns of colonization by *S. alterniflora* in a) 1973; b) 1981; c) 1992; d) 1995 and e) juvenile and mature or established *S. alterniflora* surveyed in 2001. Arrows indicate location of new colonization areas.

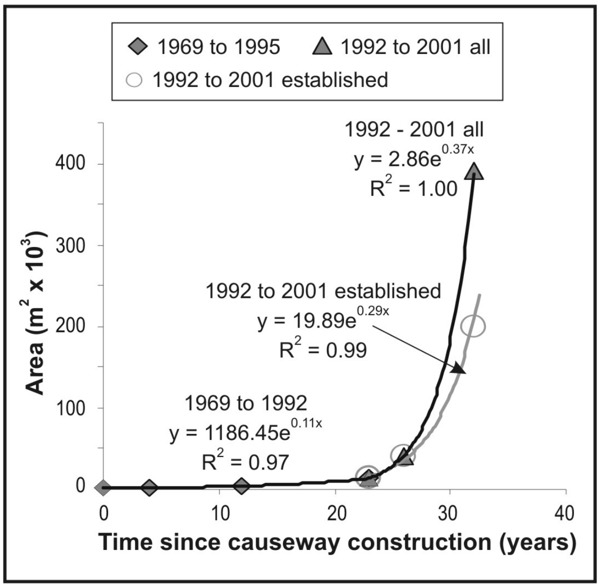

Figure 6. Change in marsh area since causeway construction divided into three classes: vegetation 1969 1992, 1992 to 2001 restricted to established vegetation only for 2001 survey and 1992 2001 based on both established and new vegetation.

begin to understand the relationship between the Highway 101 causeway construction, the development of a salt marsh ecosystem and the mechanisms of *S. alterniflora* colonization.

Observations on the distribution of *S. alt.* colonies and satellites on the Avon River mudflats support previous observations on the colonization and development of salt marshes in temperate latitudes. The survival of *S. alt.* is dependent on sedimentation to bring the mudflat surface to an elevation less than 1.8 m below the mean high water mark in a tidal system (SCHWIMMER and PIZZUTO, 2000). The Highway 101 causeway has changed the extent of tidal inundation in the Avon River estuary since its construction. The 1975 high water mark (HWM), observed in Hanstport, nine km from the causeway, was 0.5 m lower during spring tide than the spring HWM level in 1969 (AMOS, 1977). With a reduction in tidal inundation, there is a reduction in the tidal flow and an increase in siltation. The equivalent of 20 years of natural siltation occurred in the estuary within 7 years after the causeway was constructed. (AMOS, 1977). The highest monthly sediment accretion values measured within the study area by AMOS (1977) correspond directly to the location of the initial clear group of *S. alt.* satellites deposited due to ice rafting processes in 1992. Once these colonies became established, the vegetation would enhance the accretion process, and enable the vegetation to spread via rhizome growth.

Approximately 40% of rhizome growth occurs in the top 5 cm of the mudflat surface (SMART, 1982), and can be disturbed and distributed by ice movement in estuaries (GALLAGHER *et al*., 1983). As water in the mud freezes, it expands and lifts mud and rhizome material, forming raised blocks of ice and mud on the mudflat surface (Figure 7). These frozen masses or ice cakes, are less dense than fluid water and can be rafted with the rising tidal water and deposited on higher sections of the mudflat or salt marsh (GORDON and DESPLANQUE, 1983; DESPLANQUE and BRAY, 1985; OLLERHEAD *et al*., 1999). If the required conditions exist, fragmented *S. alt.* rhizomes in the ice mass can establish as a satellite community (GALLAGHER *et al*., 1983). *S. alterniflora* then have the ability to rapidly colonize uninhabited adjacent mudflat surface through rhizome growth (REDFIELD, 1971).

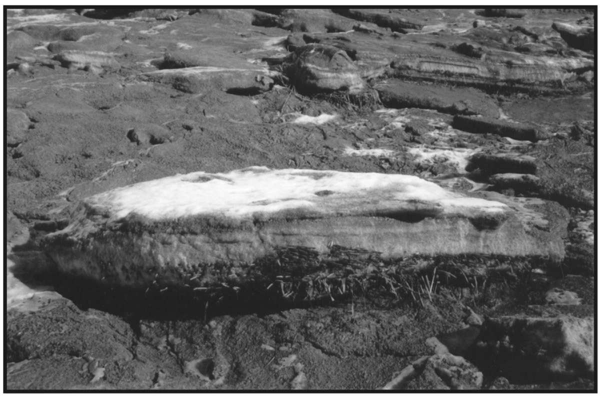

Figure 7. Ice cake containing rhizome material stranded after spring tide in January 2002.

This process is clearly observed in Figure 5c and 5d. The influence and available energy of ice rafting in the study area is supported by the observation of two isolated boulders measuring 1.25 m^2 on average on the mudflat surface and numerous deposits of coarse sediments and cobbles. These could only have been deposited through the process of ice rafting. Although wave action will dislodge and erode sections of marsh vegetation from marsh cliffs along the St. Croix and Avon River banks, the ability for waves alone to transport the material is next to impossible given the macro tidal conditions and large variations in intertidal topography.

Spatial analysis of the aerial photographs and the trend in Figure 5 indicate that the early 1990s represented a pivotal period in the rate of change in marsh area, with a change from 11% to 37%. This may be a result of consolidation of the mudflat surface around this time period, approximately 20 years after the construction of the causeway. In addition, it is likely that the marsh surface had risen to a position within the tidal frame which would enable the stranded colonies to colonize the surface and not be removed at the next spring tide nor be inundated for more than 12 hours per day. As more and more vegetation became established, the mudflat surface became more stabilized and will continue to do so. The current erosion trend occurring on the NE portion of the mudflat will likely continue over the next few years until vegetation has become established in the region. The current rate of growth of *S. alterniflora* is likely to continue unless there is: 1) more erosion of the mudflats from natural forces of tides, waves and current, decreasing the available substrate; 2) less tidal inundation transporting less sediment over areas of new growth to provide suitable surface for established colonization and 3) destructive disturbances from Highway 101 causeway modifications.

CONCLUSIONS

Impacts to hydrological processes and the overall ecological important of salt marshes were not well understood at the time of Acadian dike development or even during the construction of the Highway 101 Windsor causeway in 1969. The formation of dikes and the causeway resulted in the destruction of intertidal habitats upstream of the barrier. However, this study documents a positive impact of the causeway, the establishment of a thriving salt marsh ecosystem. Although a salt marsh may have eventually developed in the area if the causeway had not been built given the configuration of the shoreline, the barrier altered the sediment dynamics of the region such that the likelihood and rate of establishment by *S. alterniflora* increased dramatically. The development and growth rate of *S. alterniflora* on the Avon River mudflats, increasingly contributes to the productivity of the Bay of Fundy through the export of stem detritus and provides a large resting and feeding area for migratory bird species.

By combining GPS technology, used during the field research, with GIS for visualization and quantification, the overall rate of growth and mechanisms of dispersal of *Spartina alterniflora* since causeway construction were modelled. Accurate field data and simulation models of changes in saltmarsh area and rate of growth will contribute to base knowledge and an understanding of the complicated inorganic and organic relationships that exist in the estuarine ecosystem modified by human action. In addition, this study clearly depicts the importance and role of ice in stimulating the colonization of barren mudflats by salt marsh vegetation in temperate locations.

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