Investigating the role of elevated salinity in the recession of a large brackish marsh in the Fraser River estuary

by

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Abstract

At least 160 ha of the Sturgeon Bank low marsh in the Fraser River delta died off between 1989 and 2011. Humans have heavily modified the Fraser River estuary since the late 1800's, including installing a series of jetties throughout the leading edge of the delta to train the course of the river. I established a reciprocal transplant experiment to determine the role of elevated salinity in the marsh recession and generate information needed to eventually revegetate areas of receded marsh as part of an intergovernmental collaboration to investigate the causes of this marsh recession. I propose specific actions to better monitor, maintain, and restore the Fraser River delta foreshore brackish marshes in response to ongoing ecological degradation of the estuary. The predicted effects of climate change and sea-level rise may cause us to rethink options for restoring the Sturgeon Bank marsh.

Keywords: marsh recession; brackish marsh; restoration; Fraser River; *Schoenoplectus pungens*; reciprocal transplant experiment

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List of Acronyms and Abbreviations

ATP	adenosine triphosphate
BC	British Columbia
BCIT	British Columbia Institute of Technology
CGVD2013	Canadian Geodetic Vertical Datum of 2013
FREMP	Fraser River Estuary Management Program
GPS	global positioning satellite
LWD	large woody debris
NHC	Northwest Hydraulics Consultants
PDO	Pacific Decadal Oscillation
ppt	parts per thousand
PSS-78	practical salinity scale 1978
PVC	polyvinyl chloride
SBMRP	Sturgeon Bank Marsh Recession Project
SFU	Simon Fraser University
SNJ	Steveston North Jetty
TEOS-10	thermodynamic equation of seawater - 2010
VFPA	Vancouver Fraser Port Authority

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Burnaby, April 2017

Eric Balke

Chapter 1.
Introduction

At least 160 hectares of the leading edge brackish marshes of the Fraser River delta at Sturgeon Bank, British Columbia (BC) receded from 1989 to 2011 without anyone taking note. Sean Boyd (Environment and Climate Change Canada) returned to long-term bulrush monitoring transects at the Sturgeon Bank marsh in 2011 and noticed there was no marsh vegetation where it was previously present in 1989. In response to this observation, the BC Ministry of Forests, Lands, and Natural Resource Operations partnered with the federal Department of Environment and Climate Change Canada to form the Sturgeon Bank Marsh Recession Project (SBMRP) Working Group of governmental and non-governmental organizations to investigate the cause(s) and extent of marsh recession and to use science to inform future marsh restoration efforts and management.

My master's applied research project is one part of this intergovernmental collaboration. The goal of this report is to provide recommendations for future work based on the results of a reciprocal transplant pilot project experiment I established and the techniques learned and observations made during field work. The objectives of the experiment are to (1) determine the role of elevated salinity in the marsh recession and (2) generate information needed to eventually revegetate areas of receded marsh at Sturgeon Bank.

This report is divided into four Chapters and a Summary. Chapter 1 overviews the Fraser River delta and its ecologically important leading edge brackish marshes. Chapter 2 describes the marsh recession at Sturgeon Bank by contrasting historical and current marsh conditions, identifies ecosystem stressors hypothesized to have caused the recession, and outlines desired future conditions. Chapter 3 describes the reciprocal transplant experiment, interprets possible results, and considers the implications of the experiment. Chapter 4 discusses recommendations for continuing the marsh recession investigation and monitoring, maintaining, and restoring the brackish marshes of the Fraser River delta based on field observations and techniques learned while establishing the reciprocal transplant experiment.

1.1. Fraser River Delta

The Fraser River is the largest river meeting the west coast of Canada and discharges into the Strait of Georgia in southwestern British Columbia (BC). The river is approximately 1,370 km long and drains a watershed of over 233,100 km^2 from southern and central BC (Clague et al., 1983; Hutchinson, 1988). The Fraser River has a snowmelt-driven discharge regime resulting in a dominant late May to early June freshet that comprises approximately 60% of the total annual fresh water flow into the Puget Trough (Hutchinson, 1988). Mean annual discharge is 3,400 m^3/s, with flows ranging from 1,500 m^3/s to 17,000 m^3/s (NHC, 2008) and carrying an average annual sediment load of $1.2x10^7$ m^3/yr (Thomson, 1981).

The Fraser River delta consists of a combined intertidal and supratidal area of about 1,000 km^2 formed during the 10,000-11,000 years since deglaciation (Clague et al, 1983). The Fraser River splits into the North Arm, Middle Arm, Main Arm, and Canoe Pass at the river's terminus, and thus separates Sea Island, Lulu Island, and Westham Island from the rest of the landmass (Fig. 1.1.). In 1980 it was estimated that approximately 12% of the river flowed through the North and Middle Arms while the remaining 88% of the river's flow and nearly 100% of the river's sediments were carried through the Main Arm or removed by dredging (Milliman, 1980). Several processes, including the Coriolis force and tidal drag, contribute to the net northward transport of suspended matter to the north of the Main Arm channel (Luternauer and Finn, 1983). Tidal flats at the edge of the Fraser River delta as a whole have been expanding westward for most of its history (Clague et al., 1983). The 23 km-wide delta front forms Roberts Bank and Sturgeon Bank, which are characterized by shallowly-sloped sediments forming an intertidal area of 158 km^2 that includes marshes, mud flats, and sand flats (Hutchinson, 1988; Luternauer et al., 1995). Tides are mixed, with a typical range of 5.0 m. Tidal currents typically flood to the northwest and ebb to the southeast; the former is dominant and causes sediment transport from the Fraser River to be deflected to the northwest (Thomson, 1981; Atkins et al., 2016). Depending on the flow of the Fraser River, the salt wedge reaches up to New Westminster, while the river is tidally influenced upstream to Mission and Pitt Lake (Clague et al., 1983).

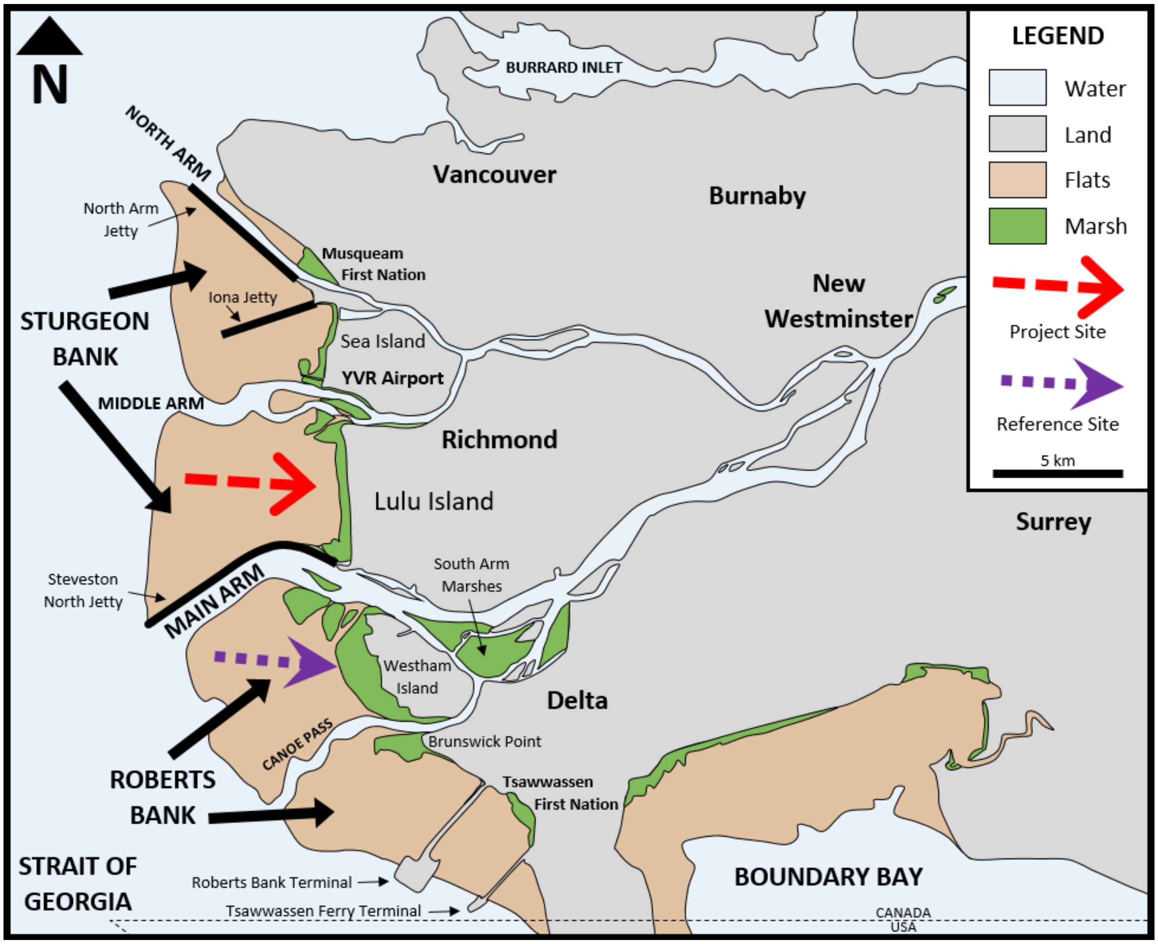

Figure 1.1. **Map of the Fraser River delta and the leading edge brackish marshes. Modified from Marijnissen (2017).**

The Fraser River delta is a mosaic of highly productive ecosystems. The estuary traps ecologically important nutrients from the marine environment, adjacent land, and aquatic and terrestrial environments of the entire watershed (Hoos and Packman, 1974). The marshes and tidal flats annually receive approximately 12,700,000 m^3 of sediment and 450,000 tonnes of organic matter from the Fraser River (Schaefer, 2004). This results in large expanses of shallow sand, mudflat, and intertidal marshes that support diverse and abundant invertebrate communities; these invertebrates are consumed by fish, wildlife, and marine mammals (Williams et al., 2009). The estuary is part of the Pacific flyway in which over 250 species of birds are observed on an annual basis, and thus the estuary is of hemispheric importance for migrating shorebirds. Marsh vegetation contributes organic material to support a large biomass of shellfish, fish, and wildlife (Schaefer, 2004). The Fraser River is the world's largest free-flowing salmon river and produces over 50% of BC's salmon (Ashley, 2006).

Humans have occupied the Fraser River delta for at least two thousand years. Prior to the arrival of Europeans, Halq'eméylem-speaking people, the Stó:lō, established large villages and towns throughout the Fraser Valley and delta where humans were an integral component of ecological systems. Nevertheless, many Euro-Canadian colonizers and their descendants have continued to think of the land as unused and unoccupied prior to their arrival. The Stó:lō people used the Fraser River as a busy artery for transportation and trade of dried fish, dried bulbs and roots, shellfish, and canoes. The major feature of the local economy was the Stó:lō relationship with salmon. Tributary streams to the Fraser River were the fishing property of local villages and extended families who harvested coho (*Oncorhynchus kisutch*) and chum salmon (*O. keta*) runs with weirs and traps. Large runs of chinook (*O. tshawytscha*) and sockeye salmon (*O. nerka*) were fished in the main river with large pursuing trawl nets extended between pairs of canoes. Sturgeon (*Acipenser medirostris* and *A. transmontanus*) and eulachon (*Thaleichthys pacificus*) were also captured using mesh nets, while the former was hunted with specialized harpoons that enabled a fisher to reach bottom-lying sturgeon at depths greater than 15 m. Fish were commonly dried within communal houses for trade and consumption as an important food source in winter. The salmon runs attracted First Nations of several different languages to the Fraser River where the people regularly congregated in the hundreds and used seasonal fishing villages. Diseases, such as smallpox, brought to North America by European colonists devastated the Stó:lō to the extent that there are presently approximately 6,000 registered Indians affiliated with 29 bands out of 2.5 million inhabitants throughout the lower Fraser River valley Stó:lō area (Kew, 2004).

The Fraser River estuary has been heavily modified since the start of European colonization of the lower Fraser River valley (Table 1.1.). The proportion of wetland area throughout the lower Fraser Basin decreased from 10% to 1% from 1827 to 1990 (Boyle, 1997). Almost all of the seasonal wet meadows, bogs, and floodplain forest throughout the delta have been converted for agriculture, industrial development, and rapid urbanization, while only the outer brackish wetlands and salt marshes remain relatively intact (Kistritz, 1992; Fig. 1.1.).

Table 1.1. Summary of major historical influences on Sturgeon Bank and river training structures near the front of the Fraser River delta constructed from 1886 to 2000 (Atkins et al., 2016; Church and Hales, 2007).

Date	Event	Purpose / Implications
1800s to present	Dredging commences	Sediment removal, channel deepened
1886-1893	No. 1 Dam construction	Prevent Main Arm from moving south; no longer exists
1888-1894	No. 2 Dam construction	As No. 1 Dam, which it superceded; no longer exists
1894	Largest documented flood (>1948)	Large sediment pulse
1900-1904	No. 3 Dam construction	Control north side of Main Arm, close Hayseed Slough; later removed
1900?	Ewens Slough Dam construction	Closed slough across Westham Island
1906 to present	Dike construction	Flood prevention, flood sediment distribution restricted
1910-1913?	Duck Island Wing Dams construction	Divert flow north to protect Westham Island; obsolete
1912-1932	Steveston North Jetty construction	Control north side of Main Arm, improve navigation channel across tidal flats; channel stabilized, marshes isolated from sediments
1913	North Arm dredging	Sediment removal, channel deepened
1914-1917	North Arm Jetty construction	Control south side of North Arm, extend channel across tidal flats; channel stabilized, marshes isolated
1922-1936	Woodward Training Wall construction	Control south side of Main Arm; promote channel scour to reduce dredging requirement
1925-1927	Woodward Dam construction	Close Woodward Slough channel
1925-1929	Steveston Wing Dams construction	Three dams to deflect flow toward Main Arm; promote accretion of Steveston Island
1930s	South Jetty construction	Channel constricted, marshes isolated
1930-1932	Steveston South Jetty No.1 construction	Prevent drainage to south and promote scour; obsolete
1935	Steveston North Jetty construction	Channels constricted, marshes isolated
1935-1936	Albion Dike No. 1 construction	Replace Steveston South Jetty No. 1; obsolete
1936-1940	Albion Dike No. 2 construction	Replace Albion Dyke No. 1
1948	Flood of record	Large sediment pulse
1949	Kirkland Island Bifurcation construction	Limit flow into Ladner Reach
1951	North Arm Jetty extension	Channel stabilized further westwards
1954	Nechako diversion	Fraser River watershed area reduced
1954	Steveston South Jetty No. 2 construction	Extension to Albion Dyke No. 2; restrict drainage to the south from Main Arm
1954	Steveston Rock Dam construction	Prevent Cannery Channel from silting; partially removed 1956
1955	Sapperton Wing Dams construction	Divert flow into main channel; protect booming grounds
1960	Steveston Island Shearboom construction	Keep debris out of Cannery Channel; obsolete
1961	Iona causeway constructed	Natural sediment regime altered
1972	Large flood	Large sediment pulse
1973-75	Trifurcation works completed	Natural flow and sediment regime altered
1978 to present	Steveston North Jetty reconstruction	Water and fish (and sediment) released onto Sturgeon Bank
Late 1990s	Borrow dredging reduced	Sediment removals reduced
2000	Steveston Bend Low Level Gabions construction	Prevent undermining of Steveston North Jetty
2007	Large flood event	Large sediment pulse

1.2. Delta Leading Edge Brackish Marshes

Tidal marshes occurring within the lower Fraser River estuary are defined by the prevailing salinity regime (i.e., fresh, brackish, or salt marshes) and characterized by distinctive vegetation zones generally occurring over a vertical gradient. The salt wedge and degree of fresh and salt water mixing is a fundamental structural element that contributes to species composition and dominance throughout the estuary. Substrate elevation determines the extent and duration of tidal inundation, and thus also influences the amount of salt water to which plants are exposed (Adams, 2002). These intertidal areas are the connectors between upland influences and tidal forces, from which most nutrients are derived from upland sources (Hessen, 1999; Nedwell et al., 1999).

The leading edge land masses of the Fraser River delta terminate in dikes followed by low gradient foreshore brackish marshes and seaward mud and sand flats. From smallest to largest area, the leading edge brackish marshes comprise the foreshore marshes off the west coast of Brunswick Point, Sea Island, Lulu Island[1], and Westham Island (Fig. 1.1.). These marshes provide the first line of effective coastal defence against storms by dissipating wave energy before reaching the dikes (Church and Hales, 2007). All four brackish marshes are legally designated as Wildlife Management Areas and managed by the provincial government.

The leading edge brackish marshes experience some of the greatest daily, seasonal, and inter-annual variations in salinity and water level of all the marshes throughout the estuary. These marshes experience changing salinities largely influenced by proximity to the river channel, the amount of mixing with fresh water, and the Fraser River flow rate. Ambient water practical salinities can range from 0 – 20[2] within a single

[1] The brackish marsh at Lulu Island is henceforth referred to as the Sturgeon Bank marsh to match with convention used by the provincial and federal governments.

[2] Salinity is reported in the literature using several different scales. The most recent standard (i.e., SI unit) for the properties of seawater is the thermodynamic equation of seawater – 2010 (TEOS-10) for which absolute salinities are expressed in grams per kilogram of solution (g/kg). The unitless practical salinity scale 1978 (PSS-78) requires the use of electrical conductivity measurements to estimate the ionic content of seawater. Knudsen salinities were developed using titration-based techniques in the early twentieth century and are expressed in parts per thousand (ppt or ‰) (IOC, SCOR, and IAPSO, 2010). Limnologists and chemists often define salinity in terms of mass salt per unit volume (i.e., g/L) (Wetzel, 2001). Salinity measurements using each of these scales have approximately equal values; a sample of seawater with a PSS-78 practical salinity of 35.0 will have a Knudsen salinity of 35.00 ppt, a TEOS-10 absolute salinity of approximately 35.2 g/kg, and a limnological salinity of approximately 35 g/L (IOC, SCOR, and IAPSO, 2010). Throughout this manuscript I report values of salinity using the scales of measurement with which each value was recorded.

tide cycle at marshes not in close proximity to the river (B. Gurd, unpublished data). These brackish marshes are generally within the oligohaline (i.e., practical salinities of 0.5 to 5) to mesohaline (i.e., practical salinities of 5 to 18) range of salinity (Dahl, 1956). Weather and prevailing winds influence the amount of fresh and salt water mixing, and these factors also influence the duration of marsh inundation. For example, strong and persistent westerly winds slow water from draining the leading edge brackish marshes and flats during the ebb tide (Marijnissen, 2017; E. Balke 2016, personal observation). The late spring freshet comprises 80-85% of the annual flow of the Fraser River and approximately 80% of the annual sediment discharge (Milliman, 1980). This discharge of large quantities of fresh water and sediments into the estuary occurs at the time of maximum growth for vascular deltaic marsh plants (Hutchinson, 1988).

Certain plants dominate the brackish marshes, especially at lower elevations, because they are able to cope with the physiological stress of high salinities and prolonged periods of tidal inundation. These plants are able to tolerate such conditions and gain a competitive advantage over other plants (Adams, 2002). Additional factors determining patterns of vegetation zonation include substrate texture and soil moisture content (Hutchinson, 1982).

All four brackish marshes share similar characteristic species of marsh plants. The lowest elevations are characterized by a monospecific stand of *Schoenoplectus pungens* (common three-square bulrush). This low marsh community transitions into a similarly distinct low to middle marsh stand of *Bolboschoenus maritimus* (seacoast bulrush) at marshes with greater salinity (e.g., the Sea Island or Sturgeon Bank marshes) or *Carex lyngbyei* (Lyngbye's sedge) at marshes with lower salinity (e.g., the Westham Island marsh). Species in the middle to high marsh compose a mosaic of clones of *Schoenoplectus tabernaemontani* (softstem bulrush), *Triglochin maritima* (sea arrowgrass), *Argentina pacifica* (Pacific silverweed), *Distichlis spicata* (seashore saltgrass), *Deschampsia cespitosa* (tufted hairgrass), and *Typha latifolia* (broadleaf cattail) (Adams, 2002; Karagatzides and Hutchinson, 1991; Hutchinson, 1982; Boyd, 1983; Moody, 1978). However, systematic vegetation surveys of all leading edge brackish marshes have not been conducted within the last 43 years (Yamanaka, 1975; Burgess, 1970). Low marsh *S. pungens* and *B. maritimus* communities composed the majority of plant biomass in the leading edge brackish marshes of the Fraser River delta and 39% of all tidal marshes in the entire estuary prior to marsh recession (Hutchinson, 1988).

These foreshore brackish marshes are extremely productive ecosystems. Large quantities of detritus from the dead aboveground parts of marsh plants form an important part of the food chain that includes many species of crabs, clams, osmoregulating juvenile and adult Pacific salmon (*Oncorhynchus* spp.), and waterfowl. The marshes produce a rich collection of invertebrates (e.g., chironomids, *Daphnia* spp., harpaticoid copepods, and amphipods) eaten by juvenile salmon, Pacific staghorn sculpin (*Leptocottus armatus*), starry founder (*Platichthys stellatus*), and stickleback *(Gasterosteidae* spp.), that are in turn consumed by great blue herons (*Ardea herodias*) and bald eagles (*Haliaeetus leucocephalus*). The rhizomes and seeds of *S. pungens*, *B. maritimus*, *C. lyngbyei*, and *S. tabernaemontani* in the low- to mid-marsh are eaten by Lesser snow geese (*Chen caerulescens caerulescens*), dabbling ducks (*Anas* spp.), trumpeter swans (*Cygnus buccinator*), and tundra swans (*Cygnus columbianus*), while marsh wren (*Cistothorus palustris*) and red-winged blackbirds (*Agelaius phoeniceus*) nest in the mid- to high-marsh (Schaefer, 2004).

1.2.1. Schoenoplectus pungens

Schoenoplectus pungens (Vahl) Palla var. *badius* is an emergent herbaceous sedge that grows in shallow fresh to brackish shores, marshes, lakes, and fens. The name *Scirpus americanus* was misapplied to *S. pungens* for many years because of the difficulty to delineate between species belonging to the small "*Scirpus americanus* complex" (i.e., *Schoenoplectus americanus*, *S. pungens*, and *S. deltarum*). This likely contributes to inconsistent use of the correct scientific name for this species throughout the literature (Ball et al., 2003). *S. pungens* is a culturally important resource for various indigenous peoples across North America; this species is used for a variety of material and cosmetic purposes (Stevens et al., 2012; Harwell, 2015; Moerman, 1998).

S. pungens grows in soils ranging from coarse gravels to clays and is an early colonizer of Pacific Northwest estuary marshes with unstable accreting sediments, high wave energy, and tidal fluctuations. *S. pungens* is a long-lived perennial that reproduces clonally and sexually, though reproduction from seeds accounts for less than 1% of shoots. The majority of plant biomass consists of below-ground coarse anchoring roots and fine roots most abundant near the stem base. A rhizome annually produces one or more above-ground vertical stems 15-150 cm tall and 0.1-0.6 cm wide (Fig. 1.2.). Dense below-ground biomass allows *S. pungens* to stabilize sediments and withstand wave erosion, while above-ground biomass facilitates sediment and nutrient accumulation, wave attenuation, and erosion control. These characteristics make this species a strong candidate for use in restoration of high-energy coastal estuarine marshes (Albert et al., 2002). Both rhizome mass and rhizome quality increased in response to the addition of

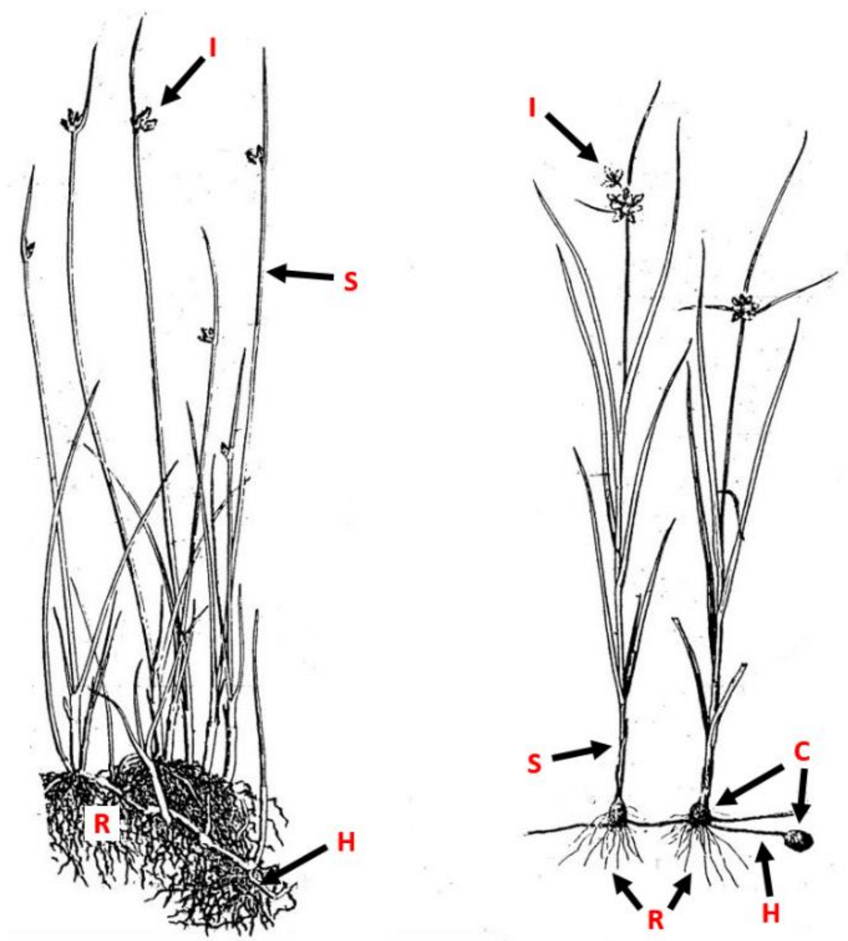

Figure 1.2. Diagram of *S. pungens* (left) and *B. maritimus* (right) illustrating inflorescences (I), shoots (S), roots (R), rhizomes (H), and corms (C). Relative height of the two plants not to scale. Modified from Karagatzides (1987).

commercial fertilizers, leading Boyd (1995) to suggest that *S. pungens* growth is limited by nitrogen. Partridge and Wilson (1987, 1988, and 1989) noted that 4 ppt is the *S. pungens* salinity for maximum growth and approximately 31 ppt is the half-growth salinity (i.e., salinity at which growth was half the maximum); however, uncertainty regarding possible nomenclature confusion and methods of the experiment likely limit the relevance of these data for the Fraser River delta marshes.

S. pungens can form dense monotypic stands on well-drained, silty-sandy substrates of relatively low moisture content within the Fraser River delta front brackish marshes. Expanding clones trap sediment causing surface aggradation and forming broad hummocks that coalesce (Hutchinson, 1982). *S. pungens* shoots begin sprouting in March, reach maximum height and start flowering in early- to mid-July, fruit in summer, and begin to senesce in August. Translocation of carbohydrates to the rhizomes is complete by October when most above-ground biomass has broken off and the rhizomes remain dormant until spring (Boyd, 1995; Boyd, 1983; E. Balke 2016, personal observation). Rhizome mass increases in July and coincides with (1) the lowest annual tides during daylight, (2) the warmest and sunniest weather, and (3) peak stem density and live stem mass (Boyd, 1995). Migratory snow geese (Boyd, 1995; Burton, 1977) and invasive resident Canada geese (*Branta canadensis*) (Dawe and Stewart, 2010; Dawe et al., 2011; E. Balke 2016, personal observation) eat lower sections of shoots and grub (i.e., excavate) below-ground rhizomes extensively. Approximately 66% of summer rhizome mass is greater than 15 cm below the substrate surface, therefore reserves of deep (i.e., >20 cm) rhizomes may be important in maintaining *S. pungens* growth when grubbing intensity is high (Boyd, 1995). Expansive near-monotypic stands and the resulting intertidal channels along the delta front support fish, shellfish, waterfowl, and other biological diversity (Boyd, 1995; Albert et al., 2002; Adams, 2002).

1.2.2. Bolboschoenus maritimus

Bolboschoenus maritimus (Linnaeus) Palla var. *paludosus* is a stout rhizomatous perennial sedge belonging to a difficult worldwide complex of sedges for which delimitation of specific and intraspecific taxa is unclear (Ball et al., 2003). It often forms expansive near-monotypic stands in low- to mid-elevations in the Fraser River leading edge brackish marshes. Stems grow 50-150 cm tall and 0.3-0.8 cm wide but are thicker and more robust than *S. pungens*. *B. maritimus* is the dominant species in middle marsh sites with finer substrates and moderately high salinity, poor drainage, and restricted fresh water influx (Adams, 2002; Karagatzides, 1987; Hutchinson, 1982). The base of the stem terminates in a firm, distinct tuber (a.k.a. corm) located 0.10-0.30 m below the marsh surface (Karagatzides, 1987). Reproduction occurs vegetatively and sexually; in the case of the former, a primary rhizome extends from the corm to form another corm from which a new shoot emerges (Fig. 1.2.) (Karagatzides, 1987). Corms act as storage organs, while rhizomes are only used for clone expansion (Karagatzides and Hutchinson, 1991; Karagatzides, 1987). Live corms are difficult to crack open and contain a solid, white core, while dead corms are relatively soft and easy to break open because they lack a solid interior core (Karagatzides, 1987). The outside husk of *B. maritimus* corms is very fibrous and can remain undecomposed *in situ* after the plant dies for several years (E. Balke 2016, personal observation). The life history and ecological function of *B. maritimus* is similar to that of *S. pungens*; however, *B. maritimus* is less extensively grazed by geese (Burton, 1977; S. Boyd 2016, personal communication) possibly because of the robust *B. maritimus* corm and stem. Rates of seed germination and growth of seedlings of both *S. pungens* and *B. maritimus* in the Fraser River delta are lower at elevated salinity levels than those of *Carex lyngbyei* (Hutchinson, 1988). While above-ground stems of *S. pungens* completely senesce and detach from the rhizome after fruiting, more-robust *B. maritimus* stems are still attached to the rhizome throughout the winter (E. Balke 2017, personal observation).

B. maritimus grown at or above the water surface (i.e., low inundation) had higher shoot survivorship, a greater number of vegetative tillers, and higher underground biomass than plants grown below the water surface (i.e., high inundation) in a controlled greenhouse experiment (Lieffers and Shay, 1981). Further, with increasing water depth *B. maritimus* had taller shoots and greater seed production. Lieffers and Shay interpret this shift from clonal growth to seed production with increasing water submergence as a strategy permitting populations of *B. maritimus* to survive through wet and dry climatic periods.

1.2.3. Phenotypic Plasticity

Both *S. pungens* and *B. maritimus* exhibit a high degree of phenotypic plasticity. Boyd (1995) documents an increase in *S. pungens* mean mass per stem and rhizome linear density (i.e., rhizome vigour) while seed production decreases with a decrease in patch density at the Westham Island brackish marsh. Boyd suggests that *S. pungens* alters the way in which it allocates resources to different plant components as patch density declines due to grubbing from geese. Karagatzides and Hutchinson (1991) conducted a reciprocal transplant experiment at the Sea Island brackish marsh for which they transplanted specimens of *S. pungens* and *B. maritimus* between the lower and higher elevations of the plants' respective distributions. The researchers found that *S. pungens* at higher elevations had greater shoot densities, flowering frequencies, and above- and below-ground masses than plants at lower elevations before transplantation. *B. maritimus* shoot density was highest at lower elevations but flowering frequency and above- and below-ground masses were greatest at higher elevations. Low elevation plants of both species with greater tidal exposure had higher shoot growth rates, while shoot mass was greatest at higher elevations and associated with larger below-ground reserves. However, high and low elevation populations of each species grew as well as residents when transplanted into new environments; both species exhibited plasticity for shoot height, mass, density, and flowering frequency, indicating these plants respond to their environment. There was still a significant effect of origin on some of the measured plant traits, suggesting a genetic component of these traits. Karagatzides and Hutchinson only transplanted within one marsh and did not compare morphological differences of these species between different marshes within the Fraser River delta. The possibility remains that there is greater genetic divergence in *S. pungens* and *B. maritimus* resulting in distinct ecotypes of these species within the different marshes of the Fraser River delta.

1.3. Leading Edge Brackish Marsh Recessions

The literature is inconsistent regarding whether or not certain leading edge brackish marshes of the Fraser River have been expanding or receding over the last 85 years. Moody (1978) describes that 90 ha of sand flats first appeared in air photos of Brunswick Point in 1948 but was densely vegetated with *S. pungens* by 1969. Subsequently, Medley and Luternauer (1976) conclude that the leading edge of the Sturgeon Bank marsh had been generally stable from 1951 to 1976. Church and Hales (2007) conclude that the engineering works to train the river (Table 1.1.) stimulated an increase in marsh expansion throughout most leading edge brackish marshes from the 1930's to 2004 by providing an increase in marsh sedimentation and increased shelter to off-channel intertidal sites. Hales (2000) deduces from air photos that construction of the river training structures on the south side of the Main Arm (a.k.a. South Jetties, i.e., Steveston South Jetty No.1, Albian Dike No.1, Albian Dike No. 2, and Steveston South Jetty No. 2) between 1930-1954 promoted sedimentation and rapid growth of marshes northwest of Westham Island. Given the rapid marsh growth following the construction of the South Jetties, Hales concludes it is likely that rapid marsh growth also followed the construction of the Steveston North Jetty (SNJ), though there exist no air photos of the Sturgeon Bank marsh prior to the start of the SNJ construction (Hales, 2000). The only areas of leading edge marsh that Hales and Church identify as having receded were the Sea Island marsh and the northern extent of the Sturgeon Bank marsh; Hales and Church further conclude that the marsh extent increased at the Sturgeon Bank, Westham Island, and Brunswick Point brackish marshes from the 1930's to 2004 (Hales, 2000; Church and Hales, 2007). From a coarse interpretation of historic air photos of the Sturgeon Bank marsh from the 1960's to 2008, Kirwan and Murray (2008) suggest that the Sturgeon Bank marsh prograded seaward near channels and was stable or slightly transgressing elsewhere.

The conclusion that each of the four leading edge brackish marshes have not receded is at odds with the most conclusive data. The first compelling evidence of leading edge brackish marsh recession comes from bulrush mapping grids in 1989 at the Sturgeon Bank, Westham Island, and Brunswick Point marshes (Boyd et al., 2012; S. Boyd, unpublished data). Boyd measured bulrush stem density at the Westham Island marsh for 28 consecutive years and observed an area of *S. pungens* and *C. lyngbyei* high elevation low marsh convert into a 55 ha mud flat by 2016 (S. Boyd, unpublished data). Boyd returned to the same mapping grids at Brunswick Point and Sturgeon Bank in 2011. At the southern margin of the Brunswick Point marsh he observed a 37.1% decrease in *S. pungens* stem density; however, he observed the greatest marsh loss at mapping grids along the marsh leading edge at the southern extent of Sturgeon Bank where 100% of 17.4 ha of *S. pungens* and *B. maritimus* marsh had died and turned into mud flat (Boyd et al., 2012). This startling observation began the SBMRP Working Group and its investigation into the extent and cause(s) of the marsh recession.

Recession of the brackish marshes is also apparent from Landsat 8 and Sentinel-2A satellite imagery. Google Earth Engine Time-lapse combines this imagery into an interactive collection of 33 cloud-free, low tide mosaics from 1984 to 2016. This timelapse imagery clearly shows the shoreward retreat of the leading edge of three foreshore marshes at Sea Island, Sturgeon Bank, and Brunswick Point between 1984 and 2008. In contrast, the leading edge of the fourth foreshore brackish marsh at Westham Island marsh remained relatively stable; however, the middle of the Westham Island marsh appears to die off and convert into a mud flat from the mid-1990's to 2016 (Google, 2017) in accordance with Boyd's observations (S. Boyd, unpublished data). Air photos from this period were taken infrequently and at different tide levels. Thus, publically available satellite imagery, though low in resolution, provides a more frequent snapshot of the extent of the Fraser River delta front marshes.

Chapter 2.
Sturgeon Bank Marsh

2.1. Historical Conditions

There are no written maps of the historical conditions of the Sturgeon Bank marsh prior to European colonization of the Fraser River delta. Musqueam and Tsawwassen people lived in the area for centuries prior to European arrival in North America. Though these Halq’eméylem-speaking Stó:lō people have a rich oral history, they did not create physical maps of the Sturgeon Bank marsh. George Vancouver made no mention of the Fraser River when first sailing past the delta during freshet in June 1792, despite making otherwise accurate maps of the Strait of Georgia and Pacific Northwest coastline (Church, 2017). Vancouver records “very low land, apparently a swampy flat, that retires several miles” with two openings (i.e., the North Arm and Middle Arm) only navigable for canoes and strewn with “logs of wood, and stumps of trees innumerable” (Vancouver, 1798). Old growth trees have since decomposed and been removed from the rivers and estuaries throughout the Pacific Northwest for navigation and shipping (Maser et al., 1988). Commercial logging practices throughout the Pacific Northwest have altered the recruitment of large woody debris (LWD) resulting in an unknown ecological impact to these estuaries (Maser et al., 1988), including the foreshore marshes of the Fraser River delta.

A series of jetties were installed throughout the leading edge of the delta to train the course of the river and may have contributed to unanticipated effects on the leading edge marshes (Table 1.1). Hydrographic charts of the area illustrate how the morphology of the Fraser River Main Arm and watercourse changed from 1827 until completion of construction of the SNJ in 1932 (Fig. 2.1.). In addition to training the Main Arm, the SNJ diverts water and sediment from the river, some of which would have been transported onto Sturgeon Bank, into the Strait of Georgia (Atkins et al., 2016). Ongoing dredging in the Main Arm removes an appreciable part of the total annual sand load delivered to the adjacent flats, and the SNJ increases resuspension of sand in the outer estuary by channelizing flow (Milliman, 1980). Hales (2000) describes how it is not possible to accurately determine marsh areas from historical maps before the advent of aerial

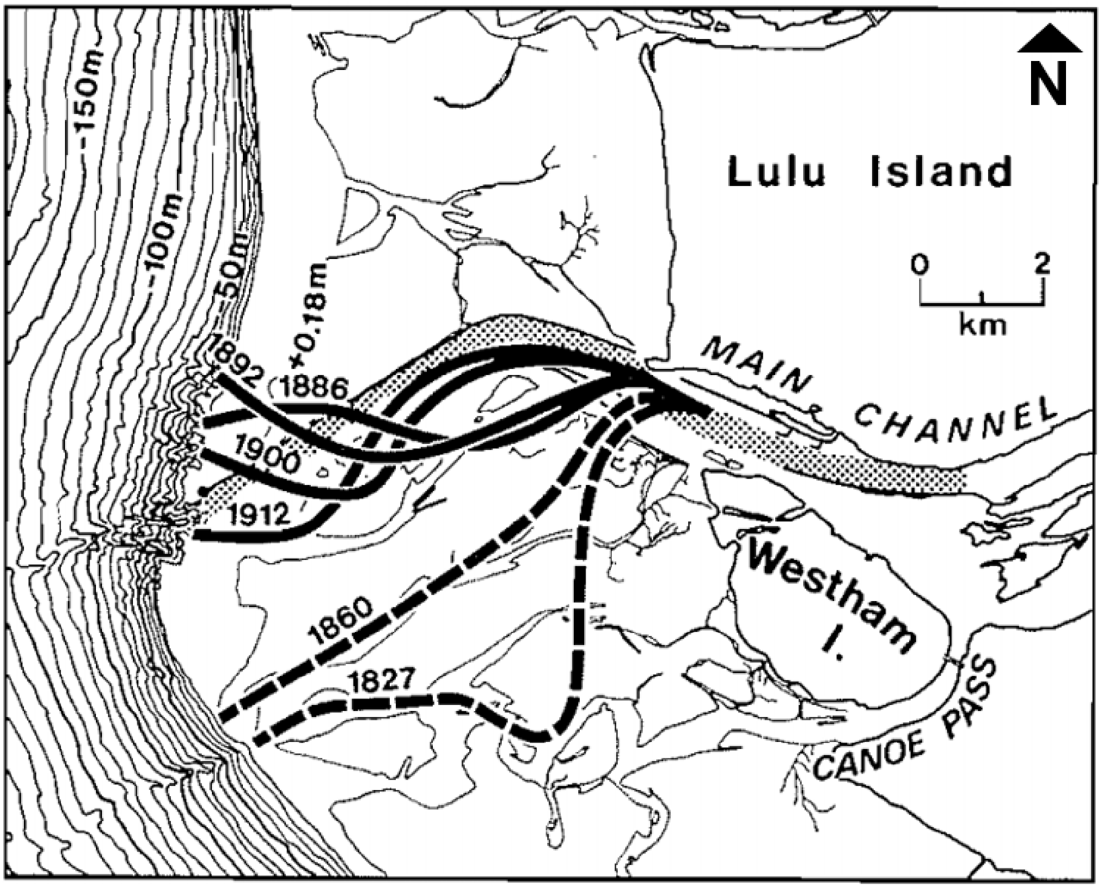

Figure 2.1. Historical changes the flow of the Fraser River Main Arm channel across the tidal flats at Roberts and Sturgeon Bank (Luternauer and Finn, 1983).

photography. The first air photos of the Sturgeon Bank foreshore marsh from 1932 are poorly resolved and difficult to distinguish marsh vegetation from tidal flats. Thus, the first accurate record of the extent of the marsh comes from air photos several decades later. It is not possible to determine the unaltered state of the Sturgeon Bank marsh due to the many anthropogenic impacts to the naturally dynamic Fraser River delta. This challenge of shifting baselines (Pauly, 1995) makes it difficult to set priorities for management and benchmarks for restoration at this site.

2.1.1. Marsh Vegetation Zonation

The most detailed vegetation map and description of the Sturgeon Bank foreshore marsh prior to recession was completed by Hutchinson (1982). The 543 ha Sturgeon Bank foreshore marsh comprised approximately 25% of the total Fraser River estuary marshes in the 1970’s (Fig. 2.2.) (Yamanaka, 1975; Boyd, 1983). Hutchinson

Figure 2.2. Oblique photos of the Sturgeon Bank foreshore brackish marsh. Photos taken 22 July 1979 looking south (top, S. Boyd) and July 2011 looking north (bottom, S. Northrup).

describes seven vegetation zones based on dominant species (Fig. 2.3.; Appendix A.) from field surveys in May-June 1978 along six transects throughout the marsh and interpretation of 1:12,000 aerial imagery (date unspecified, though most likely from 1979). He describes the pattern of vegetation zonation and species distribution is primarily linked to the elevation of the marsh platform and secondarily linked to salinity, substrate texture, and soil moisture content.

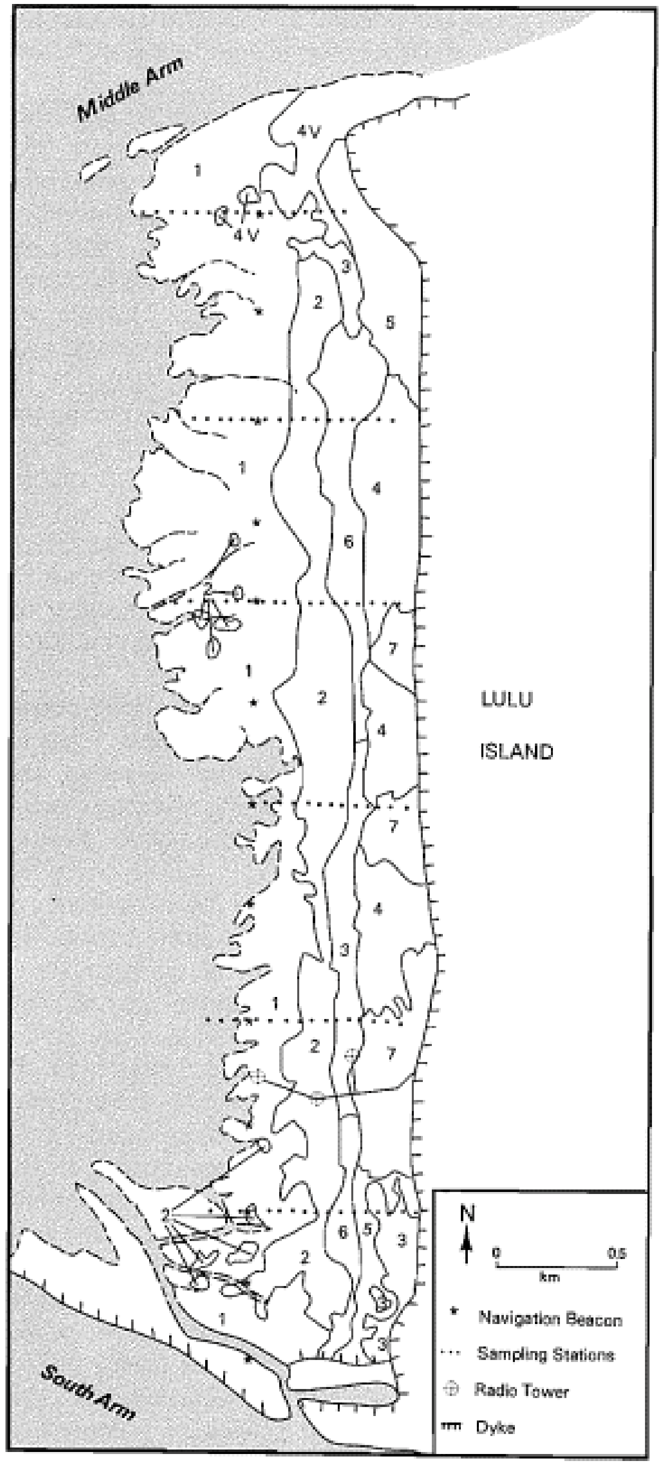

Figure 2.3. **Vegetation map of the Sturgeon Bank brackish marsh. Map based on 1978 field surveys and interpretation of 1:12,000 imagery (date not specified). Each polygon indicates area of marsh dominated by the following: (1) *Schoenoplectus pungens*, (2) *Bolboschoenus maritimus*, (3) *Carex lyngbyei*, (4) *Argentina pacifica*, (5) *Typha latifolia*, (6) *Triglochin maritima*, and (7) *Agrostis exarata* (Hutchinson, 1982).**

S. pungens was the dominant marsh species and formed dense monotypic stands at the lowest marsh elevations on well-drained, silty-sand substrates with low moisture content. Expansion of clones onto the mudflat occurred primarily along tidal channel margins and other well-drained areas (Hutchinson, 1982). Seaward expansion of *S. pungens* was greatest in the north where fresh water influence from the Middle Arm was greater (Karagatzides, 1987) and encroaching sand swells provided a supply of sand and created an area of low tidal energy (Medley and Luternauer, 1976). *S. pungens* was restricted to coarser, well-drained sediments with moderate interstitial salinity in the middle and high marsh.

In contrast, an elevation-salinity-water content interaction was more marked with *B. maritimus*. This species formed closed, sparse stands on substrates with moderate salinity and high water content in the upper extent of the low marsh. *B. maritimus* was dominant in middle marsh sites with poor drainage and restricted fresh water influx, while middle marsh sites with low salinities were dominated by *Carex lyngbyei* and *S. tabernaemontani*. Hydraulic resistance of the dense *S. pungens* leading edge stands reduces tidal energy, and thus promotes increased deposition of fine sediments that are stabilized by the growth of bulrush roots and surface microalgae. The continued accretion of silt and incorporation of plant detritus in the substrate increases water retention in the marsh at low tide and promotes invasion by *B. maritimus* (Hutchinson, 1982).

The degree to which Hutchinson's (1982) 1978 vegetation map of the entire Sturgeon Bank foreshore marsh is accurate is unknown. Hutchinson collected plants from plots along six vegetation survey transects spaced approximately 800 m apart and interpolated vegetation zonation from 1:12,000 air photos, though he does not specify which air photos he used. He does not map accumulations of LWD on the marsh and his vegetation map does not illustrate the density and abundance of non-dominant plants within each vegetation zone. Hutchinson describes the distribution of species abundances as a function of elevation and tidal variables in a separate figure; he generalizes this distribution for the entire marsh and does not discriminate how this pattern varies from the north to the south of the marsh.

To better understand the community composition of the Hutchinson's leading edge *S. pungens*-dominant vegetation zone, in August 2016 I conducted a survey for *B.*

maritimus corms at the substrate surface and subsurface at the lowest elevations of the historical leading edge of the marsh (Fig. 2.4.). I found a larger number and greater density of *B. maritimus corms* throughout the leading edge *S. pungens* stand than expected based on Hutchinson's vegetation map. After incorporating unpublished data from a 1981 vegetation survey of the same transects (Boyd, 1983; Fig. 2.4.) it appears *B. maritimus* composed a greater proportion of the low elevation leading edge marsh than described in Hutchinson's vegetation map of the Sturgeon Bank foreshore marsh (Hutchinson, 1982).

2.1.2. Salinity

Hutchinson (1982) notes a mean interstitial salinity of 10.1 ± 0.3 g/L, with a range of 3.5-15.5 g/L, during his May-June 1978 Sturgeon Bank marsh surveys. Boyd (1983) records surface salinities ranging from 0-21 ppt during his surveys from March to August 1981; salinity of water inundating the marsh decreased by half as the Fraser River flow increased as a result of the annual freshet.

2.1.3. Non-native Eelgrass

By the 1970's the Sturgeon Bank foreshore marsh had already been invaded by a non-native species of eelgrass, *Zostera japonica* (Japanese eelgrass). The first specimen of *Z. japonica* on the Pacific coast was collected in Washington in 1957 and likely introduced with oyster spat from Japan to aquaculture sites in Washington State (Harrison and Bigley, 1982). By 1974 *Z. japonica* was common in Boundary Bay, BC, and in 1979 it reached Vancouver Island (Harrison and Bigley, 1982). Medley and Luternauer (1976) characterize the area 100-400 m seaward of the southern half of the Sturgeon Bank marsh as sparse *Z. japonica*-covered organic-rich mud. They describe this non-native eelgrass as typical of the vegetation found in areas of tidal flats encroached upon by the network of drainage channels coming from the southern portion of the Sturgeon Bank marsh. In field notes from a vegetation survey in August 1981 (Boyd, 1983), Boyd notes *Z. japonica* growing on mud flats with ponding water outside the north, middle, and south leading edge of the marsh (S. Boyd, unpublished data).

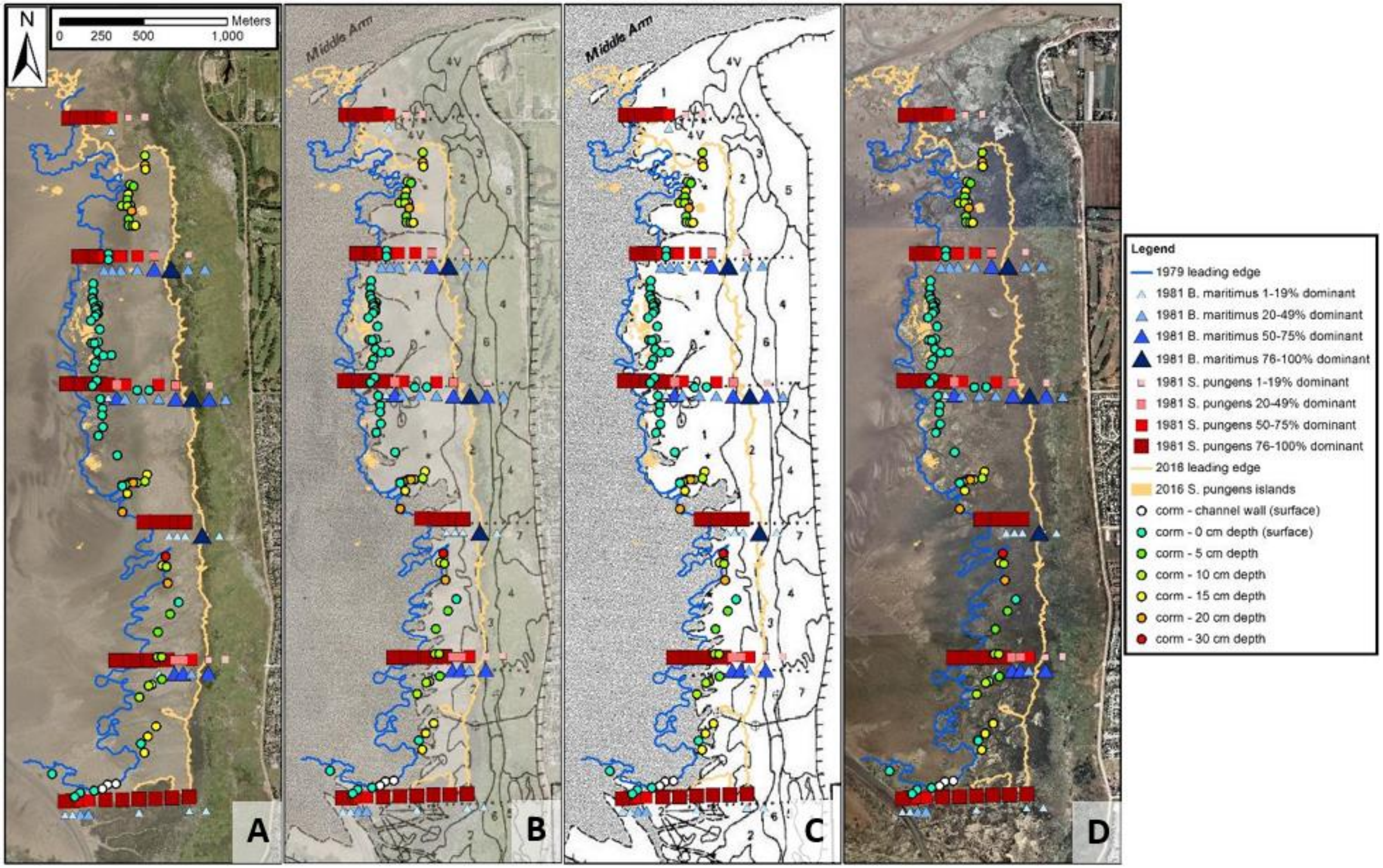

Figure 2.4. **Results of a 1981 vegetation survey and a 2016 *Bolboschoenus maritimus* corm survey at the Sturgeon Bank foreshore marsh. Polygons indicate proportion of plant community dominated by *Schoenoplectus pungens* (red squares) and *B. maritimus* (blue triangles) in 1981 (Boyd, 1983; Boyd, unpublished data); squares are offset from each survey transect 40 m north and triangles are offset 40 m south for clarity. Circles indicate locations of *B. maritimus corms* I found in 2016 at the substrate surface and at different depths. The blue line marks the approximate 1979 marsh leading edge, the beige line marks the surveyed 2016 marsh leading edge, and the beige polygons identify remnant islands of *S. pungens* (Mason, 2016). Results of surveys are overlaid on (A) a 2013 air photo (VFPA, 2013b), (B) a 2013 air photo and the georeferenced 1978 vegetation survey (Hutchinson, 1982), (C) the georeferenced 1978 vegetation survey, and (D) a 1979 air photo (BMGSB, 1979). Incorporating locations of *B. maritimus* corms from the 1981 vegetation survey and the 2016 corm survey helps us to interpret Hutchinson's 1978 vegetation map of the Sturgeon Bank marsh and the composition of the leading edge *S. pungens*-dominated community. Figure created in ArcGIS.**

2.2. Current Conditions

Tracking the Sturgeon Bank marsh recession from air photos from the 1930's to 1989 is problematic and imprecise because it is difficult to distinguish vegetated marsh from unvegetated flats; however, comparative analyses of air photos from 1979 and 2013 (Fig. 2.4.) and oblique aerial photos from 1979 and 2011 (Fig. 2.2.) unambiguously show a large marsh recession of the Sturgeon Bank marsh. Since Boyd's initial observations of the recession (Boyd et al., 2012), the leading edge of the Sturgeon Bank marsh has been mapped annually by walking the leading edge with a high-resolution Trimble Geo 7X handheld global positioning satellite (GPS) unit (Mason, 2016). I estimate that the majority of the marsh leading edge has unevenly receded approximately 200-700 m shoreward by comparing (1) the marsh leading edge in georeferenced 1979 air photos (Mason, 2016; BMGSB, 1979), (2) Boyd's 1981 vegetation survey (Boyd, 1983; S. Boyd, unpublished data), and (3) my 2016 survey of *B. maritimus* corms to the 2016 GPS field measurements of the marsh leading edge (Mason, 2016) (Fig. 2.4.). Using ArcGIS software to map these data I calculate at least 160 ha of marsh has died off since 1979, though the recession appears to have stabilized since 2011 (Mason, 2016; Marijnissen, 2017). Marijnissen (2017) describes the recession in greatest detail to date and observes that from the 1930's to early 1980's the Sturgeon Bank marsh edge was relatively stable; however, he suggests that it is most probable the retreat commenced in the 1990's and the rate of recession has decelerated since that time. Marijnissen suggests the marsh has not recovered from the recession because it passed a tipping point and established a new equilibrium.

No systematic vegetation surveys of the Sturgeon Bank marsh have been conducted since Hutchinson (1982) and Boyd (1983). The leading edge of the Sturgeon Bank marsh in 1979 was characterized by a monotypic stand of *S. pungens* (Hutchinson, 1982) but that is no longer the case. The majority of the present-day marsh leading edge consists of a variable, distinct 20-200 m wide monotypic stand of *B. maritimus* (Fig. 2.5. A). Many of these areas have relatively low densities of *B. maritimus*, particularly the lowest elevation communities (Fig. 2.5. B). The only remnant *S. pungens* leading edge monotypic stand composes the northern extent of the marsh; this area, where fresh water influence from the Middle Arm is greatest, appears to have receded least of all (Fig. 2.6.). The southern extent of the marsh surrounding the outflow of the Garry Point

Figure 2.5. **Photos of the Sturgeon Bank foreshore brackish marsh. Features of the marsh include (A) a 20-200 m wide monotypic stand of *B. maritimus* composing most of the marsh leading edge (06 July 2016), (B) low-density *B. maritimus* communities along many areas of the marsh leading edge (29 May 2016), (C) mounds of dead *B. maritimus* corms on the mud flat immediately adjacent to the marsh leading edge (06 July 2016), (D and E) remnant *S. pungens* islands on well-drained sandy substrate forming the shoreward extent of the sand swells approximately 600 m from the marsh leading edge (15 June 2016 and 29 May 2016), (F) and poorly drained mud flat colonized by *Z. japonica* between the marsh leading edge and the sand swells (03 September 2016). Photos by E. Balke.**

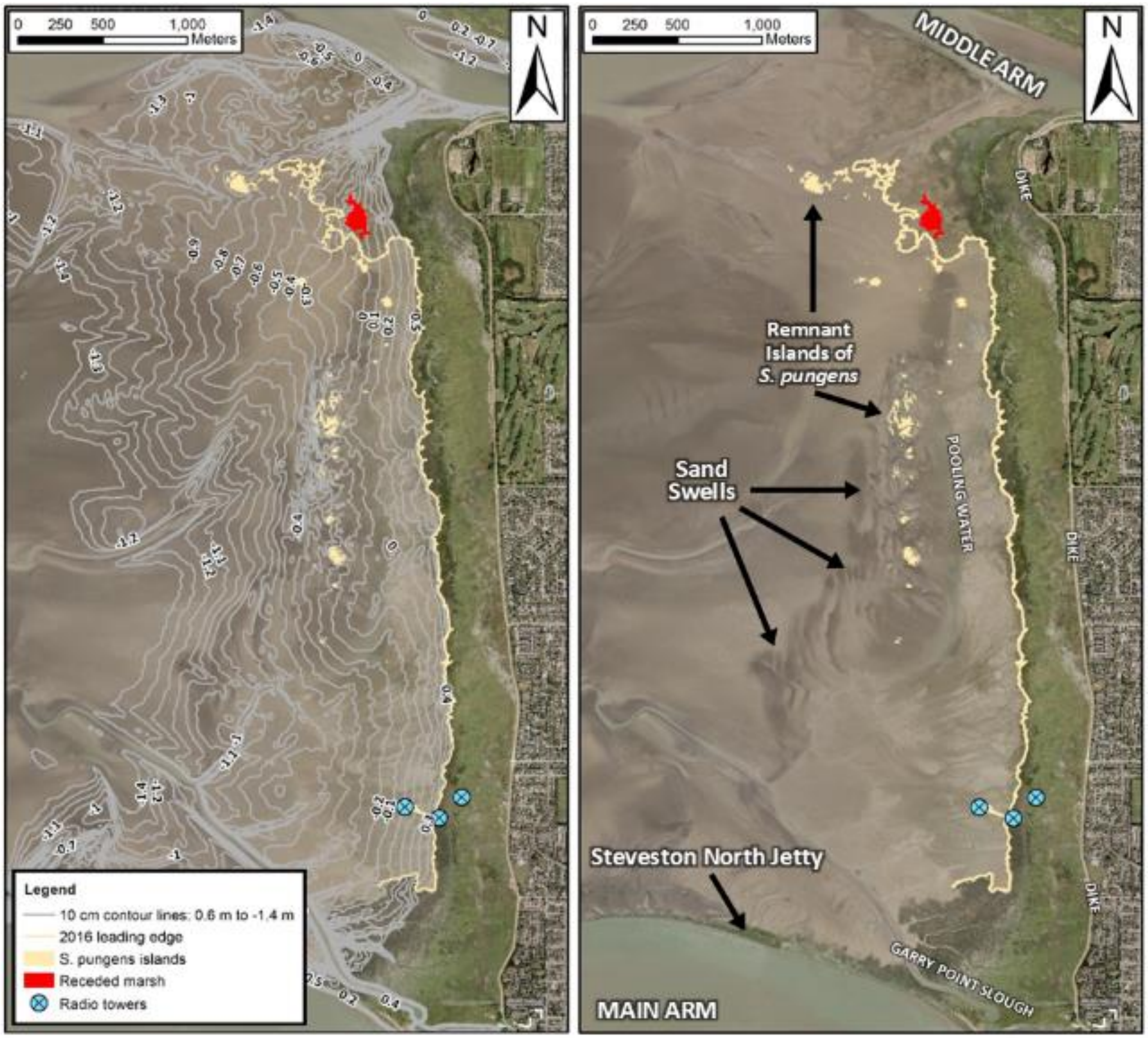

Figure 2.6. Sturgeon Bank marsh at the Lulu Island foreshore. Contour map with 10 cm-interval contour lines from 0.6 m to -1.4 m (CGVD2013 geoid) collected from lidar in 2013 are displayed in the left panel (VFPA, 2013a). Features of the Sturgeon Bank marsh are noted on the right panel. Both panels overlaid on 2013 air photos (VFPA, 2013b). Red polygon indicates an area of receded marsh converted into mud flat located shoreward of the marsh leading edge. Beige lines indicate the 2016 surveyed marsh leading edge and beige polygons indicate locations of surveyed *S. pungens* islands (Mason, 2016). Figure created in ArcGIS.

Slough is also largely intact though characterised by *B. maritimus* with pockets of *S. pungens* along the marsh leading edge (E. Balke 2016, personal observation).

Fine muds characterize the sediment immediately seaward of the *B. maritimus*-dominated marsh leading edge. Outside much of the marsh leading edge persist elevated mounds of fine sediment held together by dead *B. maritimus* corms of the receded marsh (Fig. 2.5. C). Sediment grain size increases from fine mud to coarse sand from the marsh leading edge to the western sand flats (Marijnissen, 2017; E. Balke 2016, personal observation). The eastern terminus of so-called sand swells in the middle of the flats off Lulu Island appear to coincide with the historical leading edge of the Sturgeon Bank marsh. Small monotypic stands of *S. pungens* still occupy areas of these sand swells and compose isolated marsh islands on well-drained sandy substrate approximately 600 m seaward of the marsh leading edge (Fig. 2.5. D and E; Fig. 2.4.). Medley and Luternauer (1976) first documented these sand swells in the 1970's though this feature is visible on air photos as early as the 1950's (Marijnissen, 2017). Marijnissen (2017) describes how the sand swells have been slowly moving northeast since 1986 possibly as a product of northwesterly winds reflecting off the SNJ at a 90° angle and moving the sand swells (Luternauer, 1980; Medley and Luternauer, 1976; R. Marijnissen 2017, personal communication).

The flats between the islands and the marsh leading edge are poorly drained and retain 1-5 cm of water after each ebb tide (Figs. 2.6. and 2.7.). *Z. japonica* occupies much of this ponded area of former marsh (Fig. 2.5. F), the extent of which was only preliminarily documented in 2011 (Wootton and Sarrazin, 2011). Presence of *Z. japonica* throughout areas of receded marsh indicates that the growing environment has changed greatly, perhaps to the extent that bulrush can no longer grow in there.

Both interstitial pore water and surface water salinity are greater at the Sturgeon Bank marsh compared to the Westham Island marsh. Sediment pore water salinity from flats outside the leading edge of the brackish marshes was greater at Sturgeon Bank than Westham Island in late July, 1995 (Thomas and Bendell-Young, 1999). Samples taken at 0, 6, and 20 cm depths measured practical salinities of 10, 13, and 15, respectively, outside the Sturgeon Bank marsh compared to practical salinities of 2, 4, and 5 outside the Westham Island marsh (Thomas and Bendell-Young, 1999). Boyd observed a 14-15 ppt average surface water salinity in low tide pools outside the leading edge of the Sturgeon Bank marsh and 9-10 ppt outside the Westham Island marsh in July and August 2015 (S. Boyd, unpublished data). Both pore water and low tide pool water salinity are limited characterizations of the salinity environment to which marsh vegetation is exposed. Thus, to better characterize this surface water salinity, in April 2016 we installed high-resolution water meters outside the leading edge of the Sturgeon Bank and Westham Island marshes. These meters measure salinity, temperature,

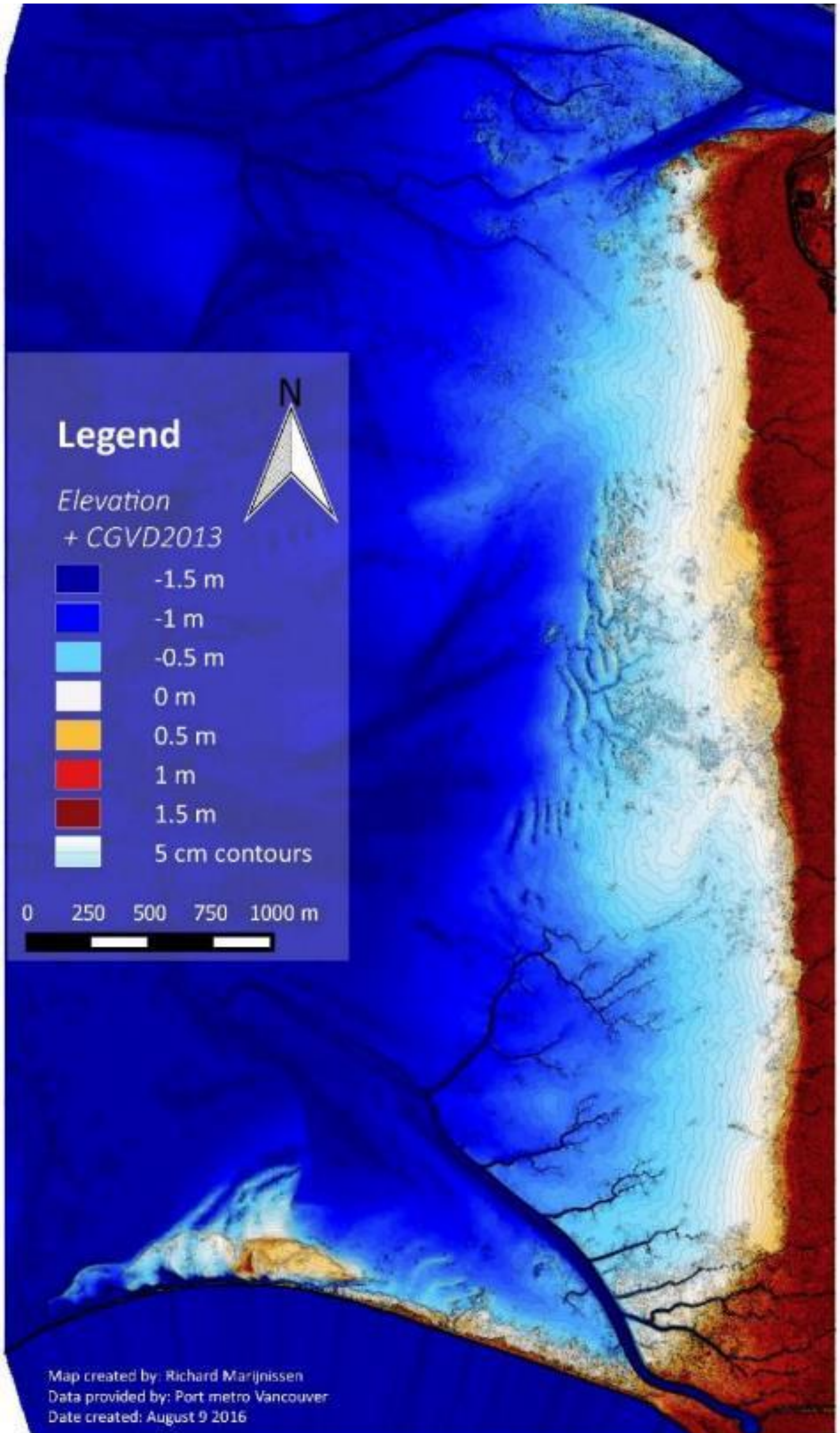

Figure 2.7. Bathymetry map of Sturgeon Bank created using 2013 lidar data (VFPA, 2013a) with the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) geoid (Marijnissen, 2017).

pressure, and total dissolved solids every five minutes. Preliminary analysis of these data indicates these marshes are exposed to a highly dynamic salinity environment. Within a single tide cycle the practical salinity of water can range from 0-20 at a single location though salinity is generally higher at Sturgeon Bank relative to Westham Island (B. Gurd, unpublished data). It is probable that the salinity is greater at Sturgeon Bank because the SNJ directs the fresh water of the Main Arm directly into the Strait of Georgia, while the Westham Island marsh receives direct fresh water input from both the Main Arm and Canoe Pass (Fig. 1.1.).

2.3. Ecosystem Stressors

The Sturgeon Bank foreshore marsh is located in one of the most heavily-developed and intensely-modified estuaries in Canada. In addition to rapid urbanization and industrialization of the delta over the last century, the construction of dikes and river training structures (Table 1.1.) have restricted the delivery of fresh water and fine sediment to the foreshore marshes. Ongoing dredging since the 1800's and construction of the SNJ at the southern extent of Sturgeon Bank from 1912-1932 may have had the greatest impact on these processes (Atkins et al., 2016). As a result of this legacy of human actions, there are many possible additional ecosystem stressors to consider that may adversely impact the Sturgeon Bank brackish marsh (Table 2.1.).

Hydrology is the dominant environmental factor affecting the structure and function of wetlands (Mitsch and Gosselink, 2007). Hydrology and substrate conditions (i.e., salinity, texture, organic matter content, and nutrient status) are the key abiotic factors that influence the development of wetland plant distributions; more specifically, intertidal wetlands are a function of their tidal hydrology, fresh water inflows, sediment inputs, sea-level rise, marsh subsidence, storm impacts, and other extreme events (Callaway, 2001).

Plants can die when respiration and the demand for adenosine triphosphate (ATP) exceed the plants' ability to photosynthesize. This occurs in tidal brackish marshes when plants are inundated too long or exposed to salinities that exceed the plants' tolerance (Mendelssohn and Batzer, 2006). There are three major impacts of flooding for plants:

Table 2.1. Possible stressors the Sturgeon Bank brackish marsh ecosystem and their probable causes.

Possible Stressors (proximate, intermediate, or ultimate)	Probable Causes	Description	References
Increased salinity (proximate)	● Steveston North Jetty (SNJ) ● Changes in freshet	● jetty directs fresh water from Main Arm into Strait of Georgia ● less freshwater delivered to foreshore marshes due to lower annual maximum flow from Fraser River	Atkins et al., 2016; Marijnissen, 2017; NHC, 2008; Morrison, Quick, and Foreman, 2002
Increased inundation (proximate)	● Ponding ● Sea-level rise ● Sand swells ● Pacific Decadal Oscillation (PDO)	● erosion of sediment, algae smothering ● longer tidal submergence ● block marsh channels, prevents water from draining	Marijnissen, 2017; Kirwan and Megonigal, 2013; Kirwan et al., 2010; Kirwan and Murray, 2008; Morris et al., 2002
Algae smothering (proximate)	● *Ulva* spp. bloom	● physical damage to bulrush stems, prevents photosynthesis, prevents porewater drainage, causes heat stress, creates anoxia and products of anaerobic decomposition	Marijnissen, 2017; Van Alstyne et al., 2015; van Hulzen et al., 2006; Nelson et al., 2003; Nelson and Lee, 2001; E. Balke 2016, personal observation
Herbivory (proximate)	● Snow geese ● Canada geese	● migratory birds in fall/spring eat bulrush stems and grub rhizomes ● invasive resident birds eat bulrush stems and grub rhizomes year-round	Boyd, 1995; Dawe and Stewart, 2010; Dawe et al., 2011; Miller et al., 1997
Altered river flow (ultimate)	● Training walls, jetties ● Diking ● Dredging ● Climate change	● directs flow of Fraser River, changes water flow across flats ● disconnects Fraser River from its floodplain, channelizes river ● changes flow rate of Main Arm, removes sediment ● changes in magnitude and timing of peak flow and annual flow	Atkins et al., 2016; Levings, 1980; Hood, 2004; NHC, 2008; Morrison, Quick, and Foreman, 2002
Reduced sediment supply (intermediate)	● SNJ ● Dredging ● Dikes/river channelization	● diverts Main Arm into Strait of Georgia, prevents deposition of sediments at Sturgeon Bank ● sediment removed from Fraser River ● increases Fraser River flow and reduces sediment deposition/retention	Marijnissen, 2017; Atkins et al., 2016; Hales, 2000
Physical damage to bulrush (proximate)	● Wrack ● Wave energy / storms ● PDO	● *Ulva* spp., large woody debris, bulrush stems ● damages bulrush aboveground biomass	Marijnissen, 2017; E. Balke 2016, personal observation
Erosion (intermediate)	● Reduced sediment supply ● Plant death ● Wave energy / storms	● from SNJ, dredging, dikes, river channelization ● dead marsh vegetation cannot retain/trap sediment ● mobilizes fine sediments and errodes marsh/flats	Williams and Hamilton, 1995; Atkins et al., 2016; Marijnissen, 2017
Removal of old growth large woody debris (LWD) (intermediate)	● Lack of old growth tree recruitment ● Manual removal ● Decomposition	● intensive logging of old growth trees, reduced recruitment of old growth trees as LWD ● LWD historically removed from river channels for navigation and collected at the Hope debris trap ● old growth LWD with root wads is an important structural component of estuarine ecosystems providing physical, chemical, and biological benefits	Maser et al., 1988
Accumulation of anthropogenically modified LWD (intermediate)	● Harvested trees escaping from log booms ● Modern logging practices	● non-old growth trees lacking root wads escape from log booms and smother marsh and damage vegetation	Maser et al., 1988
Disconnection from floodplain (intermediate)	● Dikes	● marsh unable to retreat shoreward with sea-level rise	Atkins et al., 2016; Kirwan and Murray, 2008; Hood, 2004
Excess nutrients/pollution (proximate/ intermediate)	● Pumping stations ● Pilings ● Wastewater treatment plants (WWTP)	● agricultural, urban, and industrial runoff from pumping stations at Sturgeon Bank and throughout the lower Fraser Valley ● creosote leaking from defunct radar reflectors at Sturgeon Bank, pilings throughout Fraser River ● primary and secondary effluent from five WWTP throughout the Fraser River delta	Brooks, 1995; Koepfler and Kator, 1986; Tagatz et al., 1983; Webb, 1980; Bendell-Young et al., 2004
Contaminants of emerging concern (CEC) (proximate)	● Dredging ● Urbanization ● WWTP	● polychlorinated biphynls (PCBs), polybrominated diphenyl ethers (PBDEs), heavy metals, microplastics	Meador et al., 2016; Grieve, 1977
Sudden vegetation dieback (SVD) (proximate)	● Fungal pathogens ● Nematodes ● Herbivory by marsh crabs and snails	● several hypothesized mechanisms for large-scale salt marsh dieback on the US Atlantic coast	Elmer et al., 2013
Plant disease (proximate)	● n/a	● unknown if any diseases present	

1. Root oxygen deficiency: Plants adapted to living in air receive oxygen from the substrate for aerobic respiration. When flooded, oxygen is absorbed from the substrate by roots and microbes. The absence of oxygen in the substrate creates hypoxia and decreases a plant's production of ATP thus reducing plant growth. During anaerobic metabolism toxic metabolites can be produced. Root oxygen deficiency can also lead to carbohydrate deficiency resulting in a loss of carbon for metabolic processes.

2. Soil phytotoxin accumulation: A rapid change in the biogeochemistry of soil occurs when aerobic soil is flooded. The depletion of oxygen leads to anaerobic conditions and a series of reduction-oxidation (redox) reactions that can produce compounds toxic to some plants (e.g., hydrogen sulfide and methane).

3. Postanoxic injury: Re-exposure of plant tissue to aerobic conditions after periods of anoxia due to inundation can result in severe damage. Re-exposure can produce superoxide radicals and rapid oxidation of anaerobically accumulated metabolites can increase the production of toxic intermediates (e.g., acetaldehyde) (Mendelssohn and Batzer, 2006).

There are three primary impacts to plants when they are exposed to salinities beyond their tolerance:

1. Osmotic effect: Plants exposed to salt may experience an osmotic stress that causes a water deficiency to occur. Elevated salinity of the water in the pores of the substrate can prevent the uptake of water by plants even though its roots may be immersed in water (i.e., physiological drought).

2. Toxic ion effect: The dominant ions in salt water, sodium and chloride, can exert toxic effects on plant metabolism.

3. Nutrient uptake effect: Ions in salt water may competitively inhibit the uptake of similarly charged ions needed for plant growth (e.g., sodium inhibition of ammonium uptake) (Mendelssohn and Batzer, 2006; Parida and Das, 2005).

Hutchinson (1982) reports that the interaction between elevation, salinity, and substrate water content largely determines the plant distribution of low marsh species *S. pungens* and *B. maritimus* at the Sturgeon Bank marsh. Elevation is a primary determinant of submergence and emergence periods in tidal marshes. Substrate composition (i.e., grain size and organic matter content) influences water retention and drainage in the substrate when plants are not inundated (e.g., substrates with finer particles retain more water compared to substrates with larger sized particles, such as sand). Brackish marshes may be exposed to a wide range of salinities depending on the degree of fresh and salt water mixing (Mitsch and Gosselink, 2007; Mendelssohn and Batzer, 2006; Callaway, 2001).

There are several possible mechanisms by which bulrush at the Sturgeon Bank brackish marsh may have been exposed to levels of salinity and inundation that exceed their physiological tolerance (Table 2.1.). The SNJ reduces the amount of fresh water from the Fraser River Main Arm reaching the Sturgeon Bank foreshore, and thus increases salinity levels there (Marijnissen, 2017; Atkins et al., 2016). Kirwan and Murray (2008) estimate that the rate of sea-level rise at Steveston, BC was 1.5 mm/year from 1970-1997. It is possible that diversion of sediments by the SNJ and a reduction in the amount of sediments in the Fraser River caused by dredging (Milliman, 1980) may have impaired sediment accretion at Sturgeon Bank (Williams and Hamilton, 1995), and thus prevent the marsh from offsetting the effects of sea-level rise. Inundation time may have also been affected by changes in drainage patterns due to changes in the surface morphology of the sand and mud flats (Marijnissen, 2017).

Inundation by water and its negative consequences on plant growth may also be caused by algae smothering. Large accumulations of sea lettuce (*Ulva* spp., likely *Ulva lactuca*) were present throughout the Sturgeon Bank marsh and flats in summer 2016 (E. Balke 2016, personal observation). Past surveys made no explicit mention of this type of green macroalgae (Hutchinson, 1978; Medley, 1978; Boyd, 1983). Medley (1978) makes note of a different ubiquitous long, filamentous green algae, *Melosina*, that was deposited and/or grew along tidal channels. Boyd describes thick accumulations of an unidentified algae on mud flats near the middle of the marsh leading edge in field notes from his 1981 survey; Boyd also notes mats of algae 4.5 m in diameter and 0.15 m thick causing *S. pungens* to bend over in an area of high elevation low marsh at the southern-most transect of his survey (S. Boyd, unpublished data). Though *Ulva* spp. has been observed at the Sturgeon Bank marsh in recent years and may have been present in 1981, no researchers to date have documented algae of this species accumulating at this site in such large quantities as were present throughout summer 2016 (S. Boyd 2017, personal communication). Small quantities of *Ulva* spp. appeared in May 2016 on the Sturgeon Bank flats and accumulated on bulrush shoots during the ebb tide. Large accumulations of *Ulva* spp. formed throughout the Sturgeon Bank flats and smothered *B. maritimus* along the leading edge of the marsh and *S. pungens* at some of the remnant islands from early July to September 2016 (Fig. 2.8.). *Ulva* spp. accumulations reached

Figure 2.8. Photos of leafy *Ulva* spp. algae accumulating throughout the Sturgeon Bank marsh and flats. Algae smothering (A) *S. pungens* at the remnant islands on 18 July 2016 (photo by E. Balke) and (B and C) *B. maritimus* at the marsh leading edge on 30 July 2016 (photos by D. Hogan and E. Balke, respectively).

up to 0.5 m deep along the marsh leading edge. These heavy accumulations caused physical damage to *S. pungens* and *B. maritimus* stems and appeared to prevent bulrush from photosynthesizing, promote water retention in the substrate, and increase the substrate temperature during low tide intervals. Decomposing accumulations of *Ulva* spp. created a black sludge smelling strongly of hydrogen sulfide indicating anaerobic decomposition (E. Balke 2016, personal observation). It is likely that these large accumulations of *Ulva* spp. produced poor growing conditions for the bulrush that mimic some of the effects of inundation. Bittick et al. (in review) document negative effects of *Ulva* spp. on seagrass and its epiphytes in nearby Boundary Bay while Nelson et al. (2003) document seasonal and spatial patterns of ulvoid algal blooms throughout Puget Sound. Little is known about the causes, extent, or history of such blooms in this region;

however, these problematic blooms are not associated with locations considered to be at high risk of eutrophication (Nelson et al., 2003). Leskinen et al. (2004) report that *U. compressa* is not found in coastal Scandinavian waters with salinities lower than 15 ppt but *U. intestinalis* can be found throughout the Baltic Sea except in bays with salinities below 2 ppt. As a marine algae, *Ulva* spp. in the Strait of Georgia may require high salinity water to grow, in which case the low 2016 freshet may have contributed to the uncharacteristically large bloom at Sturgeon Bank in the same year (B. Gurd 2016, personal communication).

Understanding the mechanisms of bulrush death helps us to identify possible driving factors for the Sturgeon Bank marsh recession. Since the vast majority of the plants that died are *S. pungens* and *B. maritimus*, any hypotheses proposed to explain the marsh recession should relate to plausible mechanisms that kill and limit the distribution of both plant species.

2.3.1. Recession Hypotheses

The SBMRP Working Group has proposed many hypotheses to explain the Sturgeon Bank brackish marsh recession. Many of the proposed recession mechanisms and driving factors are not independent and may have additive, compensatory, or synergistic impacts on the marsh (Fig. 2.9.). Though there may be a single cause of the recession, there may also be multiple mechanisms through which it impacts the marsh. It is very difficult to test a single recession hypothesis by conducting an experiment that isolates one of these environmental variables. It is beyond the scope of this report to comprehensively review all possible recession hypotheses and mechanisms.

Marijnissen (2017) details the most thorough evaluation of Sturgeon Bank marsh recession hypotheses to date but only tests four hypotheses and three feedback mechanisms of the marsh recession (Table 2.2.). Marijnissen concludes that none of the four hypotheses singularly explains the recession possibly because of the complex interactions between the processes. However, it is likely that several feedback mechanisms contributed to the recession after it began.

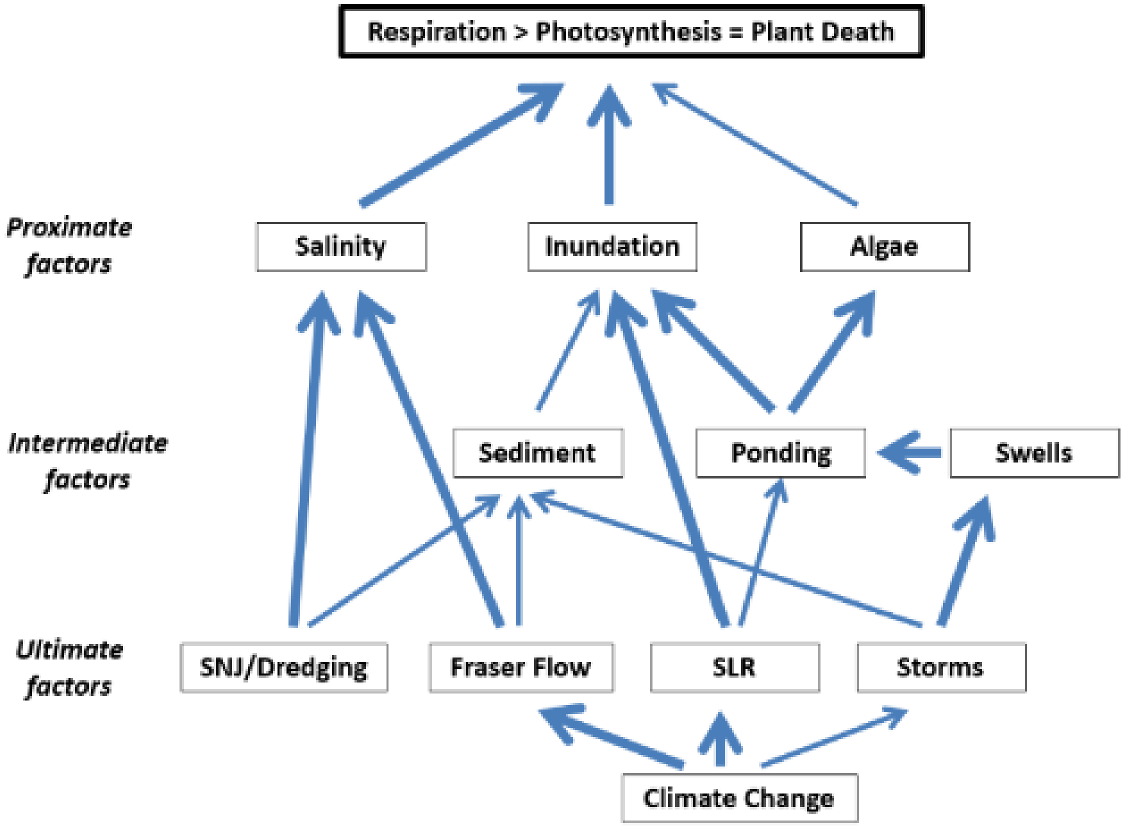

Figure 2.9. Preliminary flow chart of linkages and driving factors for the Sturgeon Bank marsh recession (SNJ = Steveston North Jetty; SLR = sea-level rise). Multiple hypothesized ultimate factors of marsh recession may cause the same mechanisms of plant death. Relative width of arrows indicate hypothesized strength of association. Figure by S. Boyd.

Marijnissen (2017) may have prematurely rejected one of the Sturgeon Bank marsh recession hypotheses. Marijnissen estimates that the local rate of net sea-level rise from 1989 to 2011 (i.e., approximately 1.85 mm/yr) would cause the marsh to retreat 2-3 m/yr shoreward in the absence of sedimentation. During this period the marsh retreated 400 m, which is one order of magnitude greater than could be attributed to sea-level rise alone. Marijnissen concludes that the current sea-level rise rate is insufficient to cause the Sturgeon Bank marsh recession therefore sea-level rise is not the primary driver of the recession (Marijnissen, 2017). Marijnissen's estimate of the rate of marsh retreat expected from sea-level rise from 1989 to 2011 is based on a linear profile of the marsh elevation from the flats to the marsh. Elevation measurements by Mason (2016) show that the elevation profile is not linear but slightly concave between

Table 2.3. Summary of potential mechanisms for the Sturgeon Bank marsh recession from Marijnissen (2017).

Recession Hypothesis	Description	Evaluation
Reduced sediment supply	• Sediment dredged from Fraser River at increasing depths, thus flow velocity and capacity to transport sediment decrease • Steveston North Jetty diverts sediment supply away from Sturgeon Bank • Sturgeon Bank flats and marsh lower • Marsh inundated for longer periods of time, plants die off, longer inudation prevents recolonization	• Hypothesis not supported • Lack of sediment supply has stabilized the bank rather than • If sediment eroded from the bed it is more likely to be deposited shoreward than to be lost to sea
Relative sea-level rise	• Sea-level rise combined with subsidence decreases elevation approximately 1.85 mm/year	• Hypothesis not supported • Without any sedimentation the marsh would only retreat 2-3 • Rate too slow to cause the 400 m recession from 1989 to 2011 • Type of structural retreat does not fit the sudden recession event observed in air photos and satellite images
Migrating sand waves	• Sand waves move shoreward as a result of storms in 2000, 2001, • Marsh receds because tidal flows obstructed • Plants inundated longer and exposed to more wave energy	• Hypothesis not fully supported • Satellite images show the marsh recession started in the 1990's before storms in 2000, 2001, and 2003
Ponding	• Repeated smothering by algae results in local loss of marsh • Exposed peat collapses and submerged by tidal flow • Because elevation locally lowered, it is more likley to be sumberged repeatedly • Biochemical alterations enable bank erosion in the pond • Process repeats until pond drained by tidal channels and conditions for biochemical erosion no longer present	• Hypothesis not supported • Examples from the literature suggest that areas of marsh killed by repeated smothering by algae fill in with sediment and are eventually recolonized by plants

the remnant *S. pungens* islands and the marsh leading edge. This concavity exists in the widest area of receded marsh and appears to enable water to pool during low tides, and thus provides ponding conditions that promote *Z. japonica* growth (Sutherland et al., 2013) (Figs. 2.6. and 2.5. F). Due to the non-linear profile of marsh elevation, the sea-level from 1989-2011 may have risen above the inundation threshold of the low marsh vegetation. An emerging idea in the literature is that there are limits to the feedbacks that preserve tidal wetlands within the intertidal zone. With rising sea-levels, coastal marshes reach a point at which they become so flooded that vegetation dies off and stabilizing ecogeomorphic feedbacks are lost (Kirwan and Megonigal, 2013; Kirwan et al., 2010; Morris et al., 2002).

2.3.1.1. Salinity Hypothesis

The SNJ directs the flow of the Fraser River Main Arm away from Sturgeon Bank and into the Strait of Georgia, and thus possibly increases salinity of water at the Sturgeon Bank marsh by decreasing the amount of fresh water mixing with salt water. Multiple investigations demonstrate that surface water and pore water salinity is, on average, greater at the Sturgeon Bank marsh compared to the Westham Island marsh (S. Boyd, unpublished data; Thomas and Bendell-Young, 1999). The salinity hypothesis suggests that the salinity of water at Sturgeon Bank has increased above the tolerance limit of *S. pungens* and *B. maritimus* resulting in the death of these plants and the recession of the low marsh at Sturgeon Bank.

2.4. Desired Future Conditions

The vegetation surveys by Boyd (1983), Hutchinson (1982), Yamanaka (1975), and Burgess (1970) provide a template for restoration and desired future conditions at the Sturgeon Bank marsh. We do not know the vegetation composition of the marsh prior to these surveys, and we do not know the extent of the marsh prior to air photos from the 1930's. Hutchinson's 1978 vegetation map most precisely delineates communities by dominant plant but does not completely describe the community diversity and extent of all plant species present. Ideally, we would aim to revegetate and restore the marsh to this state. However, these marsh communities have died off and present conditions may not be conducive to bulrush growth. Marijnissen (2017) indicates it is probable that several large-scale processes contributed to the Sturgeon Bank marsh recession thus it is possible that simply replanting areas of receded marsh according to the historical vegetation surveys may not revegetate the mud flat. It is useful to identify a relevant reference site with conditions conducive to bulrush growth to determine attainable desired future conditions to which we may restore the Sturgeon Bank marsh. Restoration projects must have some form of ecological reference for project design and from which comparison and evaluation can be conducted (Rieger et al., 2014).

2.4.1. Reference Site

The Fraser River delta is unique compared to other estuaries in the Pacific Northwest thus no appropriate reference sites for the Sturgeon Bank marsh exist outside of the Fraser River delta. The geography of the west coast of North America is not conducive to extensive marsh development except for certain locations, such as the Fraser River delta and Columbia River estuary (Chapman, 1977). Hutchinson (1988) classified the seventeen major deltas in the Puget Trough lowlands on the basis of (1) morphology and physical environments of their river basin–delta-receiving basin systems and (2) vegetation community classification. The Fraser River is regarded as unique because of the large size of its drainage basin and high exposure of the delta front. Both the Squamish River and Fraser River deltas are snowmelt-dominated, unlike the rest of the deltas in the Puget Trough that are rainfall-dominated. Thus, these two rivers have a flow regime similar to those in deltas on the central BC and southern Alaska coast. However, this similarity does not extend to plant communities. Intertidal marshes of deltas in the Gulf of Alaska consist of simple communities of *Carex* and *Puccinellia spp*. and, along with the Squamish River estuary, lack the low marsh *S. pungens / B. maritimus* communities that are a defining feature of the Fraser River delta. Hutchinson estimates that in 1988 the Fraser River delta marshes consisted of 39% low marsh *S. pungens / B. maritimus* communities; similar communities were found in the Stillaguamish (48%), Nooksack (42%), Skagit (38%), and Courtenay (25%) river deltas. Though these marshes may have similar vegetative communities to the Fraser River estuary, the rivers in which they are found do not share similar physical characteristics and flow regimes to the Fraser River. No appropriate reference sites for the Sturgeon Bank foreshore marsh exist outside of the Fraser River delta because of these physical and biological dissimilarities with nearby estuaries.

The Westham Island foreshore brackish marsh may be an appropriate reference site for the Sturgeon Bank marsh within the Fraser River delta. The Westham Island marsh has a leading edge monotypic stand of *S. pungens* that does not appear to have receded shoreward since the 1980's unlike the Sturgeon Bank low marsh. Based on Hutchinson's 1978 vegetation map (Hutchinson, 1982), the majority of the receded Sturgeon Bank marsh was composed of *S. pungens*, thus, at first glance the marsh at Westham Island appears to be an ideal reference site. Salinity should be lower at the Westham Island marsh compared to the Sturgeon Bank marsh if the salinity hypothesis is correct. This, in fact, is the case as data from multiple measurements show the pore water and surface water salinity is lower at Westham Island versus Sturgeon Bank (Thomas and Bendell-Young, 1999; S. Boyd, unpublished data). This difference may be a product of the SNJ diverting fresh water from the Main Arm away from Sturgeon Bank but still enabling fresh water to flow to Westham Island via channels and sloughs at the north end and Canoe Pass at the south end. Similarly, it is generally accepted that the SNJ reduces direct sediment deposition from the Main Arm onto Sturgeon Bank and not Roberts Bank at Westham Island (Milliman, 1980; Atkins et al., 2016; Marijnissen, 2017) though the magnitude of this reduction is unknown. Marijnissen (2017) deduces that the

Westham Island marsh is still accreting sediments, while there is no overall change in elevation at Sturgeon Bank (Marijnissen, 2017).

The Westham island foreshore marsh is not an ideal reference site because of additional differences between the Westham Island and Sturgeon Bank marshes. The Westham Island marsh extends to a lower elevation than the Sturgeon Bank marsh (Mason, 2016; Fig. 2.10.); the Westham Island S. *pungens*-dominated marsh leading edge elevation is at approximately -0.6 to -0.7 m (Canadian Geodetic Vertical Datum, CGVD2013) while the present-day *B. maritimus*-dominated Sturgeon Bank marsh leading edge is at approximately +0.5 m elevation, a difference of 1.1 to 1.2 m. The remnant *S. pungens* islands on the sand swells in the middle of Sturgeon Bank are close

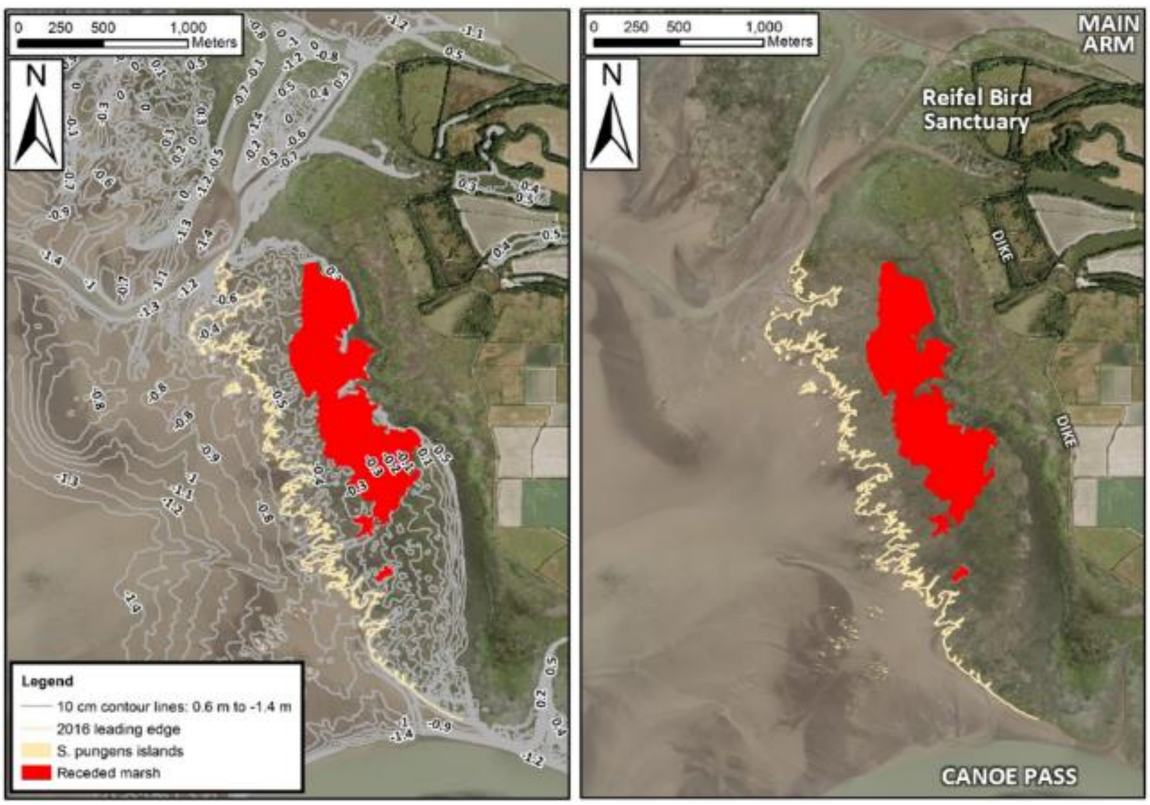

Figure 2.10. Brackish marsh at the Westham Island foreshore. Contour map with 10 cm-interval contour lines from 0.6 m to -1.4 m (CGVD2013 geoid) collected from lidar in 2013 are displayed in the left panel (VFPA, 2013a). Features of the Westham Island marsh are noted on the right panel. Both panels overlaid on 2013 air photos (VFPA, 2013b). Red polygon indicates a large area of receded marsh converted into mud flat located shoreward of the marsh leading edge. Beige lines indicate the 2016 surveyed marsh leading edge and beige polygons indicate locations of surveyed *S. pungens* islands (Mason, 2016). Figure created in ArcGIS.

to the location of the Sturgeon Bank marsh leading edge in 1978 and the seaward perimeter of these islands presently has an elevation of approximately -0.3 m (i.e., approximately 0.3 to 0.4 m higher than the present-day marsh leading edge at Westham Island). These remnant islands are only a small fraction of the marsh present in the 1970's and 1980's, and the marsh leading edge during these decades may have been lower than present day due to the encroaching sand waves and altered sedimentation. It is probable that the Westham Island marsh leading edge is tidally inundated for longer periods of time during each tide cycle because the Westham Island marsh leading edge is lower than the present-day marsh leading edge at Sturgeon Bank and possibly lower than the 1978 marsh leading edge. We have yet to corroborate this hypothesis with measurements of inundation time at both marshes.

There are distinct differences between the historical vegetation communities in the low marshes at Sturgeon Bank and Westham Island (Burgess, 1970; Yamanaka, 1975). Boyd collected *S. pungens* stem density counts at long-term bulrush monitoring plots in the Westham Island low marsh each summer for the last 28 years. Boyd recalls that the monotypic stands of *S. pungens* at the marsh leading edge in 1989 transitioned into mounds of *Carex lyngbyei*, with *B. maritimus* colonizing depressions and channels grubbed out by geese and filling with saturated, fine sediments (S. Boyd 2017, personal communication). This pattern is dissimilar from the vegetation surveys by Hutchinson (1982) and Boyd (1983) that describe the leading edge *S. pungens* monotypic stand transitioning into *B. maritimus* then *C. lyngbyei*. Boyd also observed a large area of high elevation low marsh die off and slowly convert into a 55 ha mud flat from 1989 to 2016 (Fig. 2.10.). This marsh die-off at Westham Island appears dissimilar from the Sturgeon Bank marsh recession for several reasons:

1. the Westham Island low marsh died off from the middle (i.e., mid-elevations) and expanded outward (Google, 2017), while the Sturgeon Bank marsh receded from the outside (i.e., low-elevations) toward shore (Marijnissen, 2017; Google, 2017),

2. large communities of *S. pungens* and *C. lyngbyei* have died-off at Westham Island though the Sturgeon Bank marsh recession is principally a die-off of *S. pungens* and *B. maritimus* (S. Boyd 2016, personal communication; E. Balke 2016, personal observation; Boyd et al., 2012; Boyd, 1983; S. Boyd, unpublished data; Hutchinson, 1982),

3. the Westham Island low marsh is characterized by a 300-500 m wide monoculture of *S. pungens*, but in 1981 the Sturgeon Bank marsh leading edge was characterized by a 100-200 m wide monoculture of *S. pungens* followed by a 100-500 m wide mixed stand of *S. pungens* and *B. maritimus* (Boyd, 1983; S. Boyd, unpublished data; Fig. 2.4.), and

4. the Westham Island low marsh die-off continues to expand annually and does not appear to include *B. maritimus* (S. Boyd, unpublished data; Mason, 2016) but the Sturgeon Bank marsh recession appears to have stabilized (Marijnissen, 2017).

High amounts of herbivory by snow geese and Canada geese is the leading hypothesis for the Westham Island marsh die-off (S. Boyd 2016, personal communication). Extensive rhizome grubbing by geese has caused mounds of *C. lyngbyei* at Westham Island to erode and disintegrate, allowing *S. pungens* to colonize and, in turn, also become grubbed by geese. Higher elevation areas of this marsh loss may then be colonized by *B. maritimus*. These ongoing changes observed at the Westham Island may be similar to early stages of marsh recession at the Sturgeon Bank marsh (S. Boyd 2016, personal communication).

The degree of goose herbivory may also be different between the Sturgeon Bank and Westham Island marshes, though both sites are within protected Wildlife Management Areas. The northern half of the Westham Island marsh is located in a bird sanctuary, within which hunting has been strictly prohibited since 1972 (Boyd, 1995), though hunting is still permitted outside the sanctuary in the southern half of the Westham Island marsh. Hunting was effectively prohibited throughout the Sturgeon Bank marsh in the mid-1990’s, prior to which hunting was highly restricted (S. Boyd 2017, personal communication). Waterfowl have been actively scared away from the adjacent Sea Island marsh by the Vancouver International Airport (YVR) Wildlife Management Program since the late 1980’s to reduce the number of bird strikes by aircraft (Searing, 2005). The degree to which the Westham Island marsh or Sturgeon Bank marsh may have been grazed more or less by geese is unknown.

Though the Westham Island marsh may not be a perfect reference site for the Sturgeon Bank marsh, it is nonetheless a valuable comparison. With the Westham Island foreshore marsh located on the southern side of the SNJ, the marsh still receives fresh water and sediments from the Main Arm. Thus, we may contrast this marsh with the Sturgeon Bank marsh from which fresh water and sediments are diverted.

2.4.2. Restoring the Sturgeon Bank Marsh

Many questions remain about the Sturgeon Bank marsh recession and how we might restore this valuable ecosystem. We have an abundance of hypotheses to explain the cause of the recession but it is unlikely that any one hypothesis singularly explains the recession (Marijnissen, 2017). Before restoring the marsh it is important to better understand why the marsh receded. We can do so by conducting experiments to test likely recession hypotheses. It is also possible that the recession has stopped and the stressor(s) that caused it have ceased; perhaps all that is required to restore the Sturgeon Bank marsh is to revegetate it. We also need to address some of the knowledge gaps relating to the plants that have died off and develop techniques for marsh restoration at the Sturgeon Bank foreshore. I established a reciprocal transplant experiment to address these requisite steps for marsh restoration, as described in Chapter 3.

Chapter 3.
Reciprocal Transplant Experiment

Many of the recession hypotheses and much of the investigation to date of the Sturgeon Bank marsh recession have focused on changes in sedimentation and marsh elevation. I established a reciprocal transplant experiment pilot project to address some of the knowledge gaps relating to *S. pungens* at Sturgeon Bank and techniques of revegetating the receded marsh.

The role of elevated salinity in the marsh recession has not yet been investigated, and this is the principle avenue of inquiry of the reciprocal transplant experiment. Construction of the SNJ altered the flow of the Main Arm of the Fraser River and likely consequently increased the salinity of the water reaching the Sturgeon Bank brackish marsh relative to that of the Westham Island brackish marsh. The bulrush *S. pungens* historically formed a leading-edge monoculture at the Sturgeon Bank marsh. *S. pungens* is a brackish marsh species that has a limited, but unknown, upper salinity tolerance. I hypothesize that the salinity of water at Sturgeon Bank has increased above the tolerance of *S. pungens*, and this increase in salinity has contributed the brackish marsh recession (i.e., the salinity hypothesis for the Sturgeon Bank recession). To test this hypothesis, I transplanted specimens of *S. pungens* seaward of the present-day leading edges of the Sturgeon Bank and Westham Island marshes. Since a field experiment at these sites cannot isolate the single variable of salinity, the manipulated variable is the different growing environments, of which different salinities are a significant component (i.e., the water and interstitial salinity at Sturgeon Bank is greater than that at Westham Island). If the transplanted bulrush plants have a higher survival rate at Westham Island than at Sturgeon Bank I would conclude that the environmental conditions at Sturgeon Bank are poorer for *S. pungens* growth than conditions at Westham. Thus, the salinity hypothesis would remain feasible.

Establishing the reciprocal transplant experiment provides an opportunity to test additional hypotheses that may inform methods of future efforts to revegetate and restore the Sturgeon Bank marsh. Inundation time limits tidal marsh plant growth because inundation decreases the rate of photosynthesis. Plant growth decreases and may result in plant death if respiration exceeds photosynthesis (Mendelssohn and

Batzer, 2006). Thus, plants at lower elevations are expected to be inundated for longer periods of time and therefore have a lower likelihood of survival than plants of the same species at higher elevations. I hypothesize that *S. pungens* specimens transplanted to lower intertidal elevations will grow less well than specimens transplanted to higher intertidal elevations. To test this hypothesis, I transplanted specimens of *S. pungens* across a gradient of elevations throughout the mud and sand flats at Sturgeon Bank.

There are different ecophenes of *S. pungens* at the leading edge brackish marshes of the Fraser River delta (Karagatzides and Hutchinson, 1991) that may also be different ecotypes and respond differently to transplantation. Thus, the reciprocal transplant experiment incorporates plant stock from multiple sources. I hypothesize that if there are different ecotypes of *S. pungens* present throughout the Fraser River foreshore brackish marshes that have adapted to local conditions at their harvest site, the specimens of different ecotypes will survive differently when transplanted to a similar area. To test this hypothesis, for the reciprocal transplant experiment I harvested *S. pungens* bulrush transplants from four geographically distinct areas: two from Sturgeon Bank and two from Westham Island. Considering the geographic proximity between the four harvest sites, I predict that transplants from different harvest sites will respond similarly under the same treatments, and thus all harvested plants would not be different ecotypes of *S. pungens*.

Nursery stock plants have been successfully used to revegetate tidal marshes throughout the Fraser River delta (Adams and Williams, 2004; Adams, 2002), however, nursery stock marsh plants have never been planted at the leading edge brackish marshes of the Fraser River delta. Because of the logistical challenges of mimicking tides and salinity conditions in plant nurseries, there are no plant nurseries in the Metro Vancouver area that grow marsh plants under simulated tides with brackish water; all local nursery plants are grown under fresh water conditions. I hypothesize that *S. pungens* nursery stock has a lower survival rate in the brackish tidal environment of Sturgeon Bank compared to transplants harvested from Sturgeon Bank or Westham Island.

3.1. Methods

3.1.1. Harvesting and Transplanting

We harvested and transplanted sediment cores containing *S. pungens* rhizomes with attached plant stems during low tide windows from 08 June to 07 July 2016. We harvested cores with moderate stem density (i.e., neither the lowest nor highest density at a harvest site) within five metres of the edge of the marsh. Bulrush cores were cylindrical, measuring 15 cm in depth with a diameter of 10 cm (Karagatzides, 1987). We measured stem length and number of stems for each core prior to planting. We harvested *S. pungens* cores from four locations: (1) the centre of the leading edge of the Westham Island marsh (Westham centre cores), (2) the south end of the Westham Island marsh adjacent to Canoe Pass (Westham fresh water cores), (3) the remnant marsh islands of *S. pungens* in the centre of the Sturgeon Bank marsh (Sturgeon centre cores), and (4) the north end of the leading edge of the Sturgeon Bank marsh with a large remnant marsh of *S. pungens* (Sturgeon fresh water cores). We planted all cores flush with the sediment surface. We took care to minimize manual handling of and damage to harvested cores while transporting the cores. We planted bulrush cores on the same day that they were harvested if they were harvested and transplanted at the same field site (i.e., Sturgeon Bank or Westham Island). To relocate bulrush cores between field sites (i.e., between Sturgeon Bank and Westham Island) we transported the harvested cores using a small boat with outboard motor. However, because there was only one sufficiently low tide window per day, cores relocated with the boat remained in the boat one night before being transplanted the following day. Thus, all cores from Westham Island that were transplanted at Sturgeon Bank (and vice versa) were planted one day after harvest.

Nursery stock *S. pungens* plugs were cylindrical, measuring 12 cm in depth and 3 cm in diameter (i.e., approximately 7% of the volume of sediment in a bulrush core). Peel’s Nursery in Mission, BC provided the nursery stock plugs and grew them in an organic soil matrix with fresh water. The nursery stock plugs grew from seeds harvested from *S. pungens* brackish marsh at Brunswick Point. We planted the nursery stock plugs on 01 and 02 July 2016. We did not measure stem length and number of stems for the nursery stock plugs.

3.1.2. Experimental Plots

I established two types of experimental plots for the reciprocal transplant experiment: treatment plots and control plots (Fig. 3.1.). Each treatment plot contains 20 transplanted cores (i.e., 5 cores from each of the four harvest sites at Westham centre, Westham fresh water, Sturgeon centre, and Sturgeon fresh water) and 5 nursery stock plugs arranged in a grid spaced one metre apart. Wooden stakes inserted into the ground at the top and bottom of each row of cores or plugs indicate the location of each core or plug within each row. I established each treatment plot on unvegetated mud or sand flats outside the leading edge of the marsh at Sturgeon Bank and Westham Island.

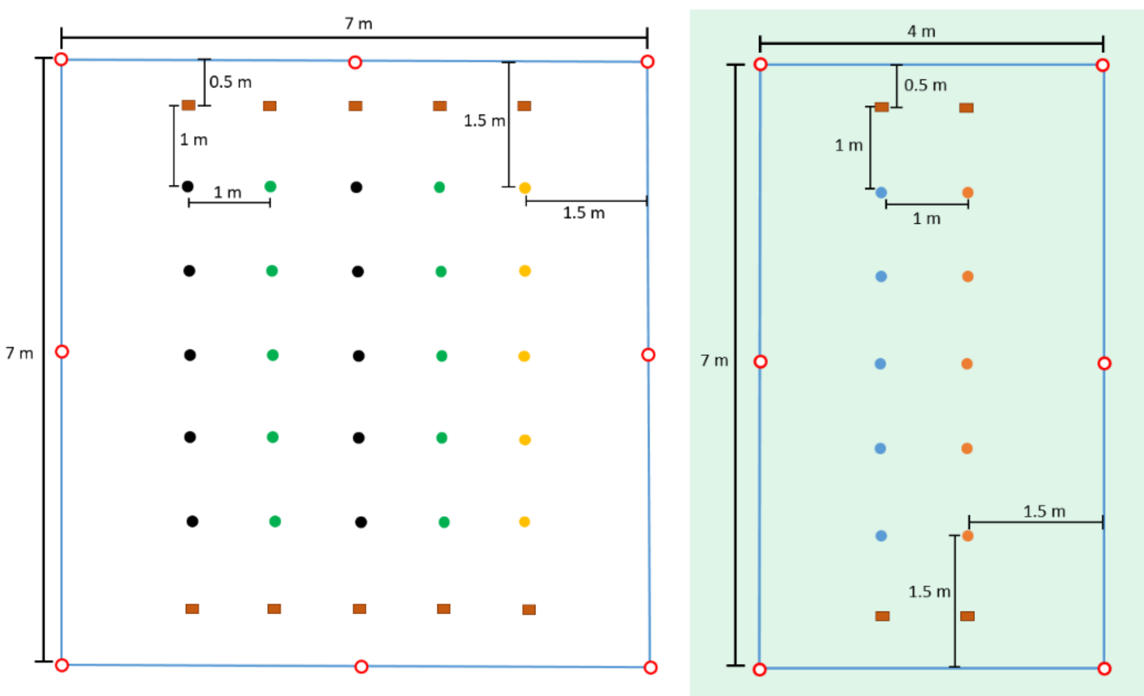

Figure 3.1. Plan view of experimental plot designs for the bulrush reciprocal transplant experiment. Bulrush cores represented by shaded circles. Treatment plot design (A) contains 10 cores from the Westham Island marsh (black circles), 10 cores from the Sturgeon Bank marsh (green circles), and 5 plugs of nursery stock (yellow circles). Control plot design (B) contains 5 cores harvested and replanted (blue circles) and 5 bulrush density and height measurements (a.k.a., non-cored controls, orange circles). Wooden stakes (brown rectangles) indicate locations of the cores and plugs. Control plots are located within existing marsh (green background), while treatment plots are located outside of existing marsh on the mud and sand flats (white background).

I established control plots within existing *S. pungens*-dominated marsh to determine whether the act of coring reduces *S. pungens* growth. Control plots are adjacent to the harvest locations of bulrush cores used in the treatment plots (Fig. 3.1.). Each control plot contains 5 cores harvested and replanted and 5 locations with bulrush density and height measurements (a.k.a., non-cored controls). Wooden stakes inserted into the ground at the top and bottom of each row of cores indicate the location of each core or density/height measurement.

After transplanting cores and nursery stock for all experimental plots, we constructed goose exclosures to prevent herbivory by Canada geese and snow geese. We constructed exclosures between 31 July and 15 August 2016 after observing evidence of grazing at several plots. Exclosures consisted of polyvinyl chloride (PVC) drain pipes inserted into the sediment around the plot perimeter with 0.0016 m (1/16'') diameter braided stainless steel aircraft cable tied between the pipes at 0.3 m and 0.6 m off the ground (Figs. 3.2., 3.3., and 3.4.).

Treatment plots are located along pre-existing transects created in 2009 by the Fraser River Estuary Management Program (FREMP). We created treatment plots at the same elevation along each of three transects at Sturgeon Bank and Westham Island (Table 3.1. and Fig. 3.5.); plots along each transect act as replicates of each treatment (n=3). The estimated average leading edge elevation of the Sturgeon Bank marsh is 0.48 m and -0.75 m at the Westham Island marsh (i.e., difference of 1.23 m elevation). At each of the three transects at Sturgeon Bank, we created a treatment plot (i) outside

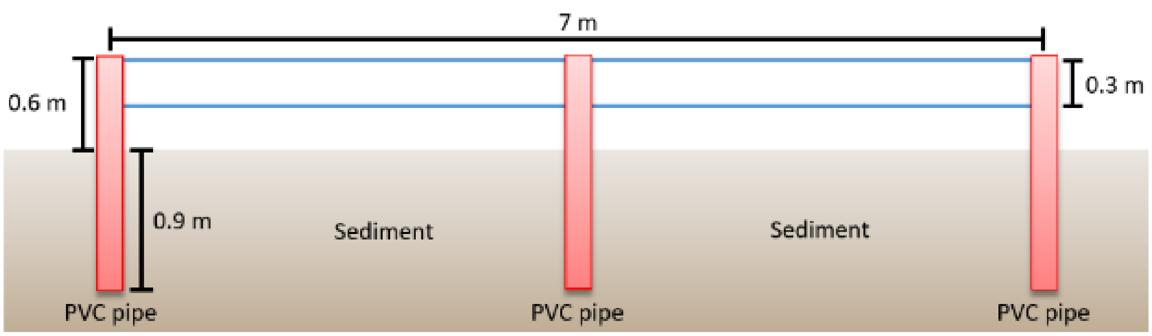

Figure 3.2. **Profile view of a goose exclosure around an experimental plot for the bulrush reciprocal transplant experiment. Red rectangles represent 0.076 cm (3'') diameter polyvinyl chloride (PVC) drain pipe inserted 0.9 m into the sediment with 0.6 m of pipe protruding above the sediment. Blue lines represent 0.0016 m (1/16'') diameter braided stainless steel aircraft cable attached to the PVC pipe 0.3 m and 0.6 m off the ground.**

Figure 3.3. Picture of a treatment plot (plot V) with goose exclosure at the leading edge of the Westham Island marsh facing northwest on 05 August 2016. Photo by E. Balke.

Figure 3.4. Picture of a control plot (CSM-3) with goose exclosure at the northern area of the Sturgeon Bank marsh facing northwest on 15 August 2016. Photo by E. Balke.

the leading edge of the marsh, (ii) at 0.31 m lower elevation than the leading edge, (iii) at 0.62 m lower elevation than the leading edge, (iv) at 0.92 m lower elevation than the leading edge, (v) at 1.23 m lower elevation than the leading edge (also equal to the average marsh leading edge elevation at the Westham Island marsh), and (vi) at 1.53 m lower elevation than the leading edge. We created a three treatment plots outside the leading edge of the Westham Island marsh adjacent to pre-existing transects. At both Sturgeon Bank and Westham Island we created three control plots along the marsh edge at locations from which we harvested bulrush cores for the treatment plots. Brad

Mason (Community Mapping Network) used a Trimble Geo 7X handheld GPS unit with a Zephyr Model 2 Antenna to determine precise elevations at both field sites to determine where to construct the treatment plots. Elevation data were differentially post-processed with Pathfinder Office software using carrier frequencies (Mason, 2016).

Table 3.1. Summary of experimental plots for the bulrush reciprocal transplant experiment. Average Sturgeon Bank marsh leading edge at 0.48 m elevation (CGVD2013). Average Westham Island marsh leading edge at -0.75 m* elevation, which is 1.23 m lower than that at Sturgeon Bank. *Note: The average Westham Island marsh leading edge estimate of -0.75 m was based on an incomplete preliminary data set; a more accurate average Westham Island marsh leading edge estimate is approximately -0.60 m.

Site	Plot Type	Plot Name	Plot Elevation (m)	Treatment Description
Sturgeon Bank	Treatment Plot	K-1	0.44	• outside Sturgeon Bank marsh leading edge • area of receded marsh
		J-1	0.41	
		I-1	0.31	
		K-2	0.17	• 0.31 m lower elevation than the average Sturgeon Bank marsh leading edge • area of receded marsh
		J-2		
		I-2		
		K-3	-0.14	• -0.62 m lower elevation than the average Sturgeon Bank marsh leading edge • area of receded marsh
		J-3		
		I-3		
		K-4	-0.44	• -0.92 m lower elevation than the average Sturgeon Bank marsh leading edge
		J-4		
		I-4		
		K-5	-0.75	• -1.23 m lower elevation than the average Sturgeon Bank marsh leading edge • average elevation of Westham Island marsh leading edge*
		J-5		
		I-5		
		K-6	-1.05	• -1.53 m lower elevation than the average Sturgeon Bank marsh leading edge
		J-6		
		I-6		
	Control Plot	CSM-1	-0.15	• control plots for Sturgeon Bank central marsh cores
		CSM-2	-0.20	
		CSM-3	-0.15	
		CSF-1	-0.53	• control plots for Sturgeon Bank freshwater marsh cores
		CSF-2	-0.47	
		CSF-3	-0.34	
Westham Island	Treatment Plot	X	-0.66	• outside Westham Island marsh leading edge
		V	-0.69	
		Y	-0.65	
	Control Plot	CX	-0.61	• control plots for Westham Island central marsh cores
		CV	-0.52	
		CY	-0.61	
		CU-1	-0.64	• control plots for Westham Island freshwater marsh cores
		CU-2	-0.60	
		CU-3	-0.58	

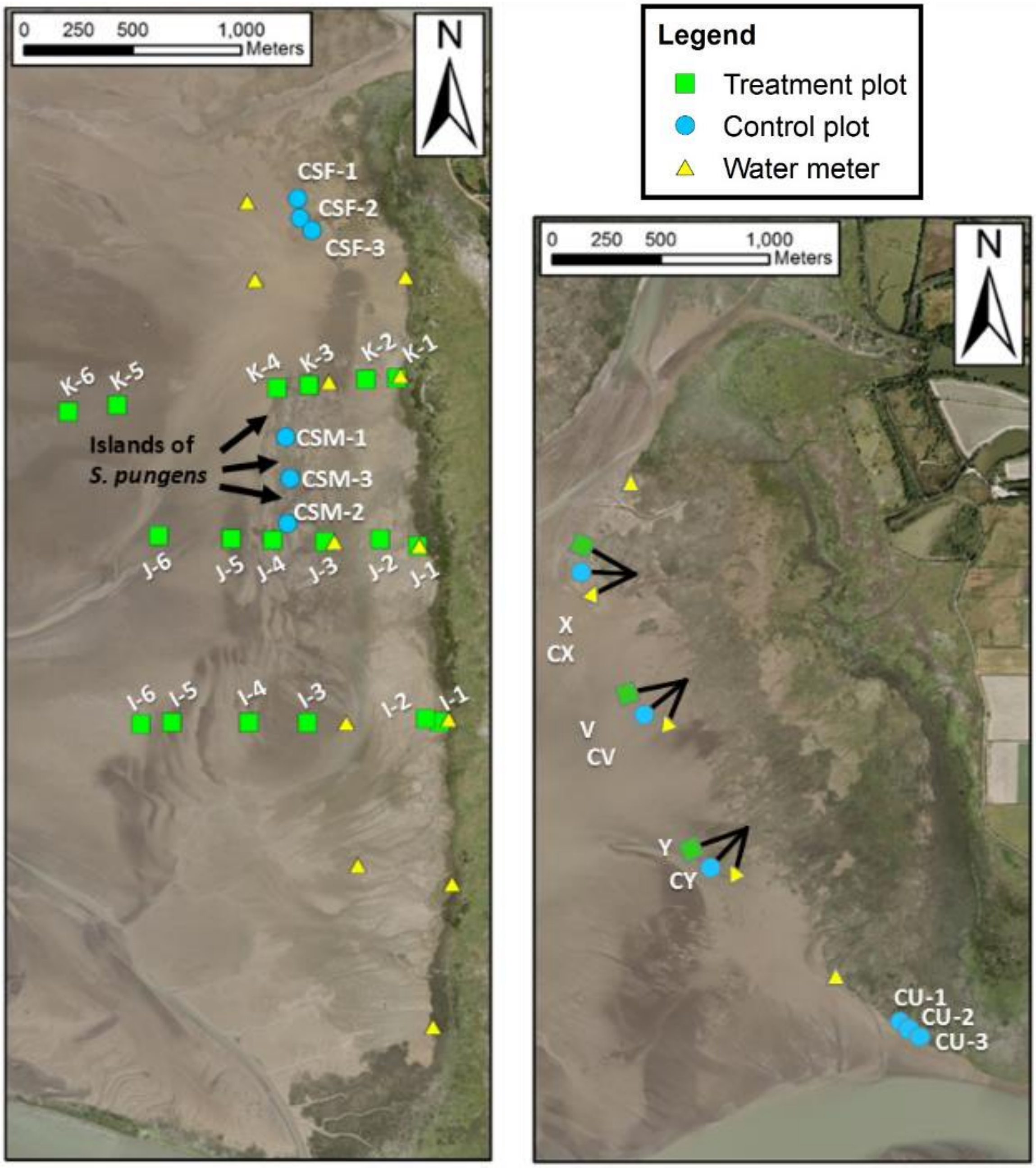

Figure 3.5. **Locations of experimental plots for the bulrush reciprocal transplant experiment at Sturgeon Bank (left) and Westham Island (right). Includes treatment plots (green squares), control plots (blue circles), and water meters (yellow triangles) displayed over 2013 air photos (VFPA, 2013b). Figure created with ArcGIS.**

3.1.3. Monitoring and Data Collection

I photo-monitored each plot every two weeks until the end of August 2016 to observe any unanticipated changes or impacts to the transplants and field sites. We also installed water meters (Instrumentation Northwest, Inc. CT2X non-vented Smart Sensor) at the leading edge marshes (i.e., 12 water meters at Sturgeon Bank and 5 meters at Westham Island; Fig. 3.5.) to measure salinity, temperature, pressure, and total dissolved solids every five minutes. These meters will help us understand how salinity varies between locations at Sturgeon Bank and Westham Island and throughout each tide cycle.

I will eventually compare survival and growth of the transplants by three parameters: presence/absence of stems, stem count, and stem length. From a similar *S. pungens* transplant experiment at Westham Island, Boyd observed (1) all *S. pungens* transplants survived and most transplanted rhizomes grew laterally after one year, (2) approximately half of transplants died after two years, and (3) all transplants died after three years (S. Boyd 2017, personal communication). Thus, the reciprocal transplant experiment will continue for three years, and final response data will be collected in June 2019. Annual data collection on stem presence, number, and length will be conducted to determine interim growth and survival of bulrush in June 2017 and June 2018.

3.2. Interpreting Results

3.2.1. Salinity Hypothesis

If an increase in salinity at Sturgeon Bank has contributed to the brackish marsh recession, then we would expect transplanted cores adjacent to the leading edge of the Sturgeon Bank marsh (i.e., plots K-1, J-1, and I-1) to grow less (i.e., fewer and shorter *S. pungens* stems during early summer re-growth) than the cores transplanted adjacent to the leading edge of the Westham Island marsh (i.e., plots X, V, and Y). However, this comparison does not control for elevation since the average marsh leading edge elevation at Sturgeon Bank is approximately 1.2 m greater than that at Westham Island. Thus, we can compare the leading edge plots at Westham Island with plots at the same elevation at Sturgeon Bank (i.e., plots K-5, J-5, and I-5) and expect transplants in these Sturgeon Bank treatment plots to also grow less than those at Westham Island.

It is still possible that other factors contributed to or caused these anticipated outcomes. For example, there may be additional aspects of the growing environment at Sturgeon Bank that are not conducive to bulrush growth. The Sturgeon Bank marsh is more exposed to winds from the northwest (i.e., greater fetch) than the Westham Island marsh, therefore wind energy, wave energy, and/or currents may be greater at the Sturgeon Bank marsh. There were much larger quantities of sea lettuce algae at Sturgeon Bank compared to Westham Island in summer 2016 (E. Balke 2016, personal observation; Section 3.3.1.1.) that may negatively affect the growth of transplants. If the SNJ deprives Sturgeon Bank of fresh water from the Fraser River Main Arm, the jetty may also deprive Sturgeon Bank of other matter important for bulrush growth (e.g., sediments of a particular size and LWD).

If transplants at the Sturgeon Bank marsh leading edge grow more than those at Westham Island, herbivory of transplants by waterfowl prior to construction of the goose exclosures may have been greater at Westham Island than at Sturgeon Bank. However, if transplants at the leading edge at Sturgeon Bank and Westham Island survive equally poorly (i.e., no transplant survival), then it is likely that the experimental design is flawed; transplanting bulrush onto mud flats where bulrush are not naturally found may indicate that the mud flats do not have appropriate growing conditions for *S. pungens* bulrush. Conversely, if transplants at both sites survive equally well, it is possible that a three-year experiment may not be long enough to evaluate bulrush survival from transplantation.

3.2.2. Elevation

If *S. pungens* has a lower likelihood of survival with increasing periods of inundation and areas of lower elevation at Sturgeon Bank have greater periods of inundation, then we would expect bulrush transplants in plots at lower elevations to grow less than those at greater elevations (i.e., K/J/I-1 survive > K/J/I-2 > K/J/I-3 > K/J/I-4 > K/J/I-5 > K/J/I-6). This result may also occur if the wind and/or wave energy is greater at lower elevations (i.e., deeper water) and if these forces stress the bulrush transplants.

Alternatively, there are several possible explanations if we observe the opposite outcome (i.e., K/J/I- 6 > K/J/I- 5 > K/J/I- 4 > K/J/I- 3 > K/J/I- 2 > K/J/I- 1). Plots closer to the leading edge of the marsh may have been grazed more heavily by geese before I constructed the goose exclosures. The substrate generally transitions from fine particles (i.e., mud) at the leading edge to larger particles (i.e., sand) with decreasing elevations (Marijnissen, 2016; Hutchinson, 1982; E. Balke 2016, personal observation); larger particles allow for less retention of water, and *S. pungens* grow well in well-drained silty-sand substrates of relatively low moisture content (Hutchinson, 1982). The benthic community may also change with elevation and/or substrate; thus, different benthic communities associated with increasing elevation in the mud/sand flats may affect *S. pungens* growth. Also, the pumping stations at the dike directly pump ditch water from the adjacent city of Richmond into the high marsh; thus, transplants at greater elevations (i.e., closer to the pumping stations) may be exposed to greater concentrations of urban pollutants.

The possibility remains that the *S. pungens* cores survive equally across the elevation gradient. This may be the case if the elevation gradient was not great enough to be biologically significant. However, this is unlikely as on 18 July 2016 my field technician and I observed the flow tide flood the experimental plots over a two-hour period. If transplants at each different elevations survive equally successfully, then perhaps there is no changing bulrush stressor across the elevation gradient. In fact, to restore the Sturgeon Bank marsh all that may be needed is to transplant cores into areas of receded marsh. A more likely outcome may be that transplanting bulrush onto mud/sand flats where bulrush are not naturally found may indicate that the mud/sand flats do not have appropriate growing conditions for *S. pungens*.

3.2.3. Ecotypes

If we harvested *S. pungens* from areas in which the bulrush have adapted to local conditions at their harvest site (i.e., genetically distinct ecotype[s]), then we would expect these transplants to have different growth/survival rates than those from other harvest sites transplanted within the same treatment. For example, if at the Sturgeon Bank leading edge plots the transplants harvested from the remnant *S. pungens* islands at Sturgeon Bank (i.e., Sturgeon middle cores) survived better than transplants from the other three harvest sites, this would support the hypothesis that the *S. pungens* from the remnant islands are a distinct ecotype. Alternatively, if transplants harvested from a particular area survive poorer than transplants from another site, this may indicate bulrush at the original harvest site may have had a disease or were harvested differently. However, considering the geographic proximity of the harvest sites to each other, I anticipate that all transplants will grow similarly at each respective treatment.

3.2.4. Coring

If coring *S. pungens* reduces the growth of transplants, then we would expect the growth of cores in the control plots to be less than the growth of the non-cored controls in the control plots. Since *S. pungens* is rhizomatous and all transplants are removed surrounded by a core of native substrate, I anticipate the act of coring and transporting bulrush will not decrease its growth over the three-year term of the experiment. In a similar experiment with appropriate controls (Boyd, 1995), Boyd observed that transplanting cores had no effect on *S. pungens* growth (S. Boyd 2017, personal communication). However, if that is not the case and coring does decrease bulrush growth, then the act of coring is a stressor for all transplants and will likely result in decreased growth in all treatment plots. Thus, if great enough, this universal stressor to all transplants may cause all cores in all treatment plots to fail.

3.2.5. Nursery Stock

Since I did not measure stem lengths and count stems of the nursery stock plugs prior to planting, the indicator of success is binary: presence or absence of above-ground growth. To evaluate the relative survival of nursery plugs, I will compare the proportion of nursery plugs that produce stems to the proportion of transplanted cores that produce stems within the same treatment. Of these two sources of *S. pungens*, whichever source has a greater proportion of plugs/cores producing stems for a given treatment will be more capable of growing within that treatment condition.

3.3. Discussion

Though the primary reason for conducting the reciprocal transplant experiment is to determine the role of elevated salinity in the marsh recession, establishing the experiment also provides many opportunities for the Sturgeon Bank Marsh Recession Project team to learn about the feasibility, techniques, and challenges of transplanting bulrush throughout the leading edge marshes of the Fraser River delta. Conducting field work at the Fraser River delta foreshore brackish marshes and flats is both physically and logistically challenging. Especially at night, it is important to be able to confidently determine work windows as determined by the tides and weather conditions. I have included a list of things to know about working at the foreshore marshes (Appendix B.) to assist future field work at these marshes. The entire project cost $41,053, the majority of which is the cost of labour ($27,672) to establish and monitor the experiment over a 12-month period (Appendix C.).

As a pilot project, the reciprocal transplant experiment enables us to identify possible confounding factors and experimental design flaws to improve future experiments and restoration projects.

3.3.1. Possible Confounding Factors

3.3.1.1. Algae

During the summer 2016 field season we observed large quantities of green sea lettuce (*Ulva spp*.) accumulating at the marsh leading edge and experimental plots at Sturgeon Bank. Although *Ulva spp.* has been observed at this site in previous years (S. Boyd 2017, personal communication), to the best of our knowledge, prior to 2016 no one has observed it accumulating in such large quantities at the Sturgeon Bank marsh. This algae grows attached to subtidal substrate (Nelson et al., 2003) and we also observed it growing attached to the sand flats at elevations below the most seaward experimental plots (i.e., -1.05 m). *Ulva* spp. can continue to grow while free floating in the water column once detached from the substrate (Nelson et al., 2003). We observed *Ulva spp.* carried shoreward by the flood tide at Sturgeon Bank where it accumulated along the leading edge of the marsh in dense mats up to 0.6 m thick starting in mid-June 2016. The algae remained highly mobile while suspended in water, and during ebb tides large quantities of *Ulva* spp. were transported seaward, with the largest transported quantities observed in drainage channels throughout the flats. *Ulva* spp. would catch on any protrusions and accumulate as it was being carried seaward by the ebb tide. In particular, *Ulva spp.* frequently accumulated at the base of stems of transplanted *S. pungens* cores and at the wooden stakes marking their locations. By early July, transplanted *S. pungens* in some plots was completely covered by *Ulva spp*. during the ebb tide, resulting in physical damage and smothering of the stems, and thus preventing the bulrush from photosynthesizing during low tide. The degree to which *Ulva spp.*

smothered transplanted cores at Sturgeon Bank varied unpredictably between tide cycles (Figs. 3.6. and 3.7.) and even between plots during the same tide cycle (Fig. 3.8.).

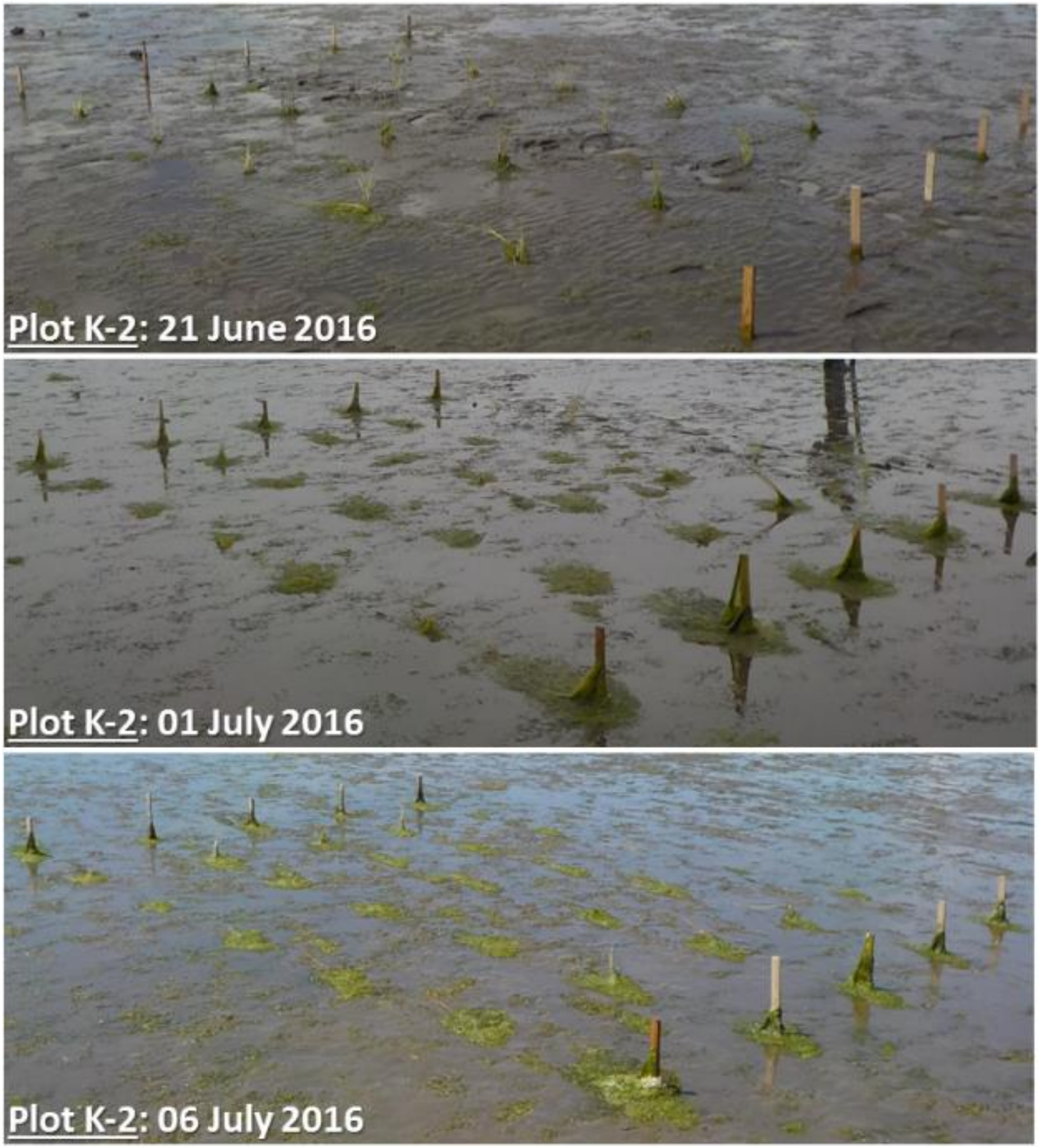

Figure 3.6. **Photos of Sturgeon Bank treatment plot K-2 from three different days throughout the 2016 summer (21 June, 01 July, and 06 July from the top to bottom). *Ulva spp.* algae (green) accumulates at the base of transplanted *S. pungens* stems and installed wooden stakes at each ebb tide. Last transplant was planted on 21 June 2016. Photos by E. Balke.**

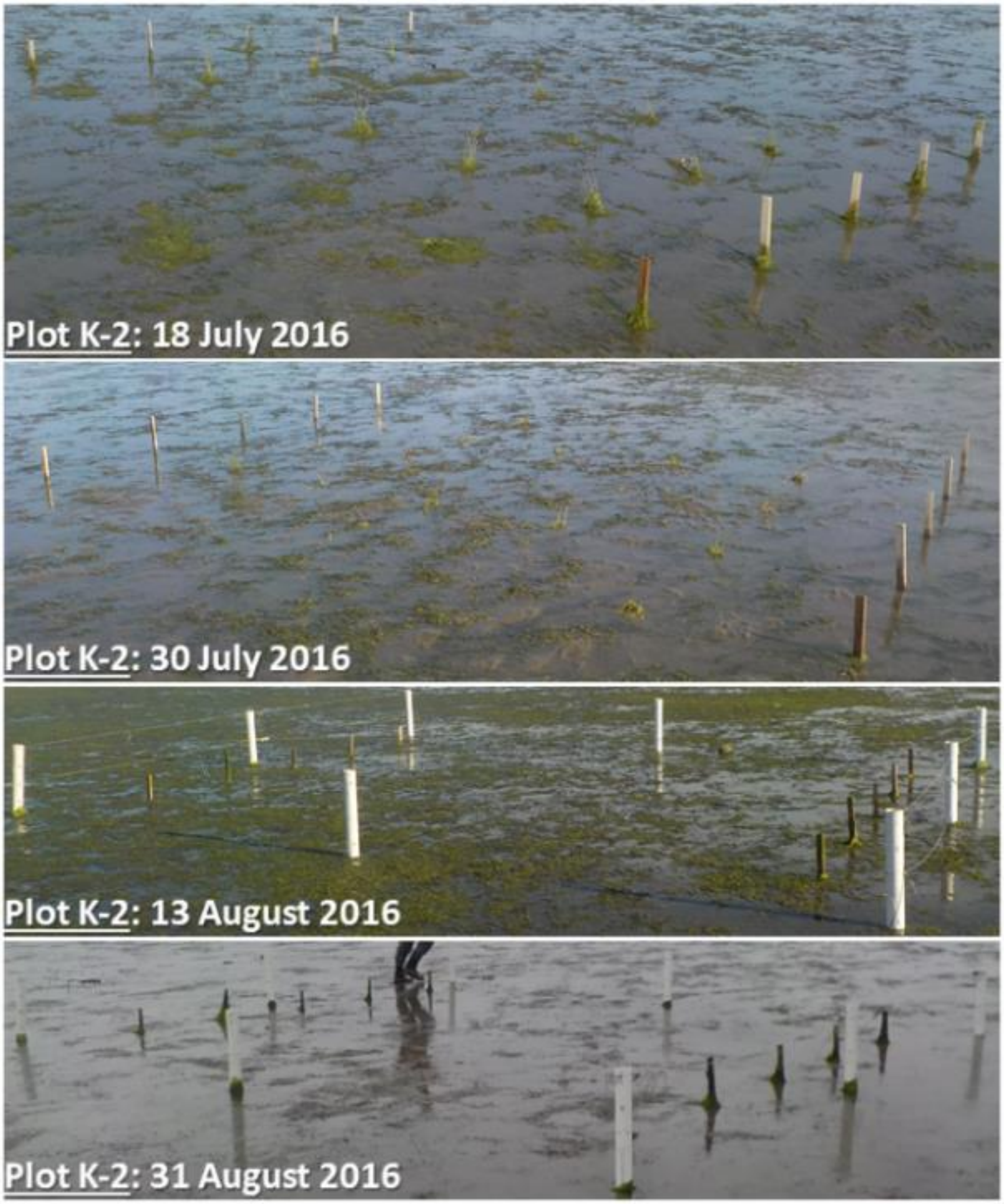

Figure 3.7. Photos of Sturgeon Bank treatment plot K-2 from four different days throughout the 2016 summer (18 July, 30 July, 13 August, and 31 August, from the top to bottom). *Ulva spp.* algae (green) accumulates throughout the plot during the ebb tide and amounts vary with each tide cycle. Goose exclosure constructed on 08 August 2016. *S. pungens* stems naturally senesce at the end of summer. Photos by E. Balke.

Figure 3.8. Photos of different treatment plots at Sturgeon Bank on 19 July 2016 and one plot at Westham Island on 21 July 2016. *Ulva spp*. algae accumulates in large quantities at Sturgeon Bank treatment plots but not at Westham Island plots in summer 2016. Photos by E. Balke.

We observed very little *Ulva spp.* at the Westham Island marsh and mud flats throughout the summer. We occasionally found small ephemeral deposits of *Ulva* spp. fronds along the leading edge of the marsh or caught in the stems of a transplanted *S.*

pungens core. However, *Ulva spp.* was clearly not present at Westham Island in the quantities and dense accumulations observed at Sturgeon Bank (Fig. 3.8.). Instead, an unidentified species of dark green filamentous algae grows throughout the Westham Island marsh. During several summers over the last decade, Boyd observed large blooms of this filamentous algae in the area of receded high elevation low marsh (S. Boyd 2016, personal communication). These observations lead him to hypothesize that such blooms may have contributed to the Westham Island marsh recession by smothering *S. pungens* and facilitating water pooling (S. Boyd 2016, personal communication).

Because of the stark contrast of *Ulva spp*. presence and absence at Sturgeon Bank and Westham Island, respectively, we surveyed adjacent areas of the leading edge of the Fraser River delta for the algae. We found large accumulations of *Ulva spp.* smothering brackish marsh at Sea Island and accumulating along the shores of Iona Beach Regional Park. In contrast, south of Canoe Pass at Brunswick Point we found small, ephemeral deposits of leafy *Ulva spp*., similar to our observations at Westham Island. It is clear from our surveys that *Ulva spp.* deposits in large quantities on the foreshore marshes of the Fraser River delta north of the SNJ, but not south of the jetty. It may be possible that the SNJ or the flow of the Main Arm of the Fraser River act as a sort of “shield” protecting Roberts Bank from *Ulva spp.* coming from the northwest. However, reasons for this accumulation pattern and algae bloom are unknown and merit further investigation, especially if *Ulva spp.* negatively impacts the leading edge brackish marshes of the Fraser River delta. The 2016 Fraser River freshet was the fourth lowest in the last 72 years (WSC, 2017); this reduction in fresh water flow may have increased water salinity, and thus contribute to the unexpectedly large accumulations of *Ulva spp*. (B. Gurd 2016, personal communication).

Hemmera (2004) surveyed accumulations of *Ulva* spp. in summer 2012 and 2013 throughout the mud flats south of Brunswick Point and in the inter-causeway area between the Roberts Bank Terminal and Tsawwassen Ferry Terminal Causeways as part of the Environmental Assessment of the Roberts Bank Terminal 2 project. Hemmera reports finding two types of *Ulva* spp. accumulations on mud flats north of the Roberts Bank causeway and in the inter-causeway area: (1) mounds of sand and mud topped with several unspecified species of *Ulva,* referred to as *Ulva* hummocks, with mean size 0.69 m^2 and (2) 0.05-0.20 m thick mats of *Ulva* spp. with mean areas of 35-100 m^2 within

10 m by 10 m plots. Based on my 2016 survey of the Brunswick Point marsh and looking at photos in the Hemmera (2004) report (Fig. 3.9.), I deduce that these accumulations of *Ulva* spp. at Roberts Bank are composed primarily of a filamentous algae (perhaps *U. intestinalis* and/or *U. compressa*) that are clearly not the same species of sea lettuce (likely *U. lactuca*) smothering marsh vegetation north of the Main Arm. It appears there are accumulations of different species of ulvoid algae along different sections of the foreshore marshes and flats of the Fraser River delta.

Figure 3.9. Photos of different types of *Ulva* spp. accumulations along the Fraser River delta front. Hemmera (2004) reports *Ulva* hummocks (A) and mats (B) (likely composed of filamentous *U. intestinalis* and/or *U. compressa*) on the flats north of the Roberts Bank Causeway and in the inter-causeway area in summer 2012 and 2013. The accumulations of *Ulva* spp. at Roberts Bank south of Canoe Pass are clearly not primarily composed of the same species as the algae (likely leafy *U. lactuca*) that smothered *S. pungens* transplants (C) and the *B. maritimus* Sturgeon Bank marsh leading edge (D) in summer 2016. Photos A and B from Hemmera (2004) and photos C and D by E. Balke.

3.3.1.2. Goose Herbivory

I found evidence of Canada geese grazing transplanted bulrush in the reciprocal transplant experimental plots within two weeks of transplanting bulrush cores. We started constructing goose exclosures around each plot on 31 July 2016, however we did not finish until 15 August 2016. Experimental plots were vulnerable to herbivory for different amounts of time, and during this period of vulnerability plots were grazed with unknown intensity. Because of the likely negative impact of *Ulva spp.* on transplants at Sturgeon Bank and the natural senescing of stems after flowering, it is impossible to attribute *S. pungens* transplants stem damage to any single cause. Conversely, stem damage observed at Westham Island treatment plots (i.e., plots X, V, and Y) (Fig. 3.10.) was more likely caused by goose herbivory because the damage occurred in the absence of large amounts of *Ulva* spp. and Canada geese were frequently observed near these plots. It is unknown the extent to which goose herbivory of transplanted bulrush will adversely affect survival of cores at Westham Island treatment plots.

Figure 3.10. Photos of treatment plot V at Westham Island on 07 July and 31 July 2016. Bulrush stems from transplants largely absent from the plot on 31 July, most likely as a product of Canada goose herbivory prior to construction of goose exclosure on 31 July 2016. Photos by E. Balke.

The original design of the goose exclosures was not sufficiently robust to withstand conditions at Sturgeon Bank. Instead of tying stainless steel aircraft cable between the erect PVC pipes, in summer 2016 I originally tied polyethylene sturgeon fishing line rated for 61 kg around each experimental plot. Upon returning to the plots on 06 October 2016, 32% of polyethylene segments around goose exclosures inspected at Sturgeon Bank were broken. I replaced these broken segments with new polyethylene line but I continued to find large proportions (i.e., 45% and 51%) of polyethylene lines broken on subsequent visits (i.e., 22 October and 14 November, respectively). Very few of the polyethylene lines were broken (i.e., 1.2%) at experimental plots at Westham Island on multiple visits (i.e., 07 October and 13 November). Throughout winter 2016/2017 I replaced all polyethylene lines with braided stainless steel, however there remains a period of time during which different plots at Sturgeon Bank were not protected from goose herbivory. All *S. pungens* had already senesced by October, making it difficult for Canada geese and migrating snow geese to locate and grub at the rhizomes of the experimental transplants, regardless of the state of the goose exclosures.

3.3.1.3. Possible Experimental Design Flaws

We were unable to install the goose exclosures immediately after transplanting *S. pungens* cores due to challenging logistics and time constraints. With future transplant experiments, it is important to construct goose exclosures before transplanting cores or, at the very least, immediately after transplanting cores to eliminate the possible confounding effect of goose grazing. The polyethylene fishing line originally used to construct the goose exclosures clearly was not strong enough, and some sort of stainless steel cable must be used in the future. However, the large proportion of polyethylene lines broken at Sturgeon Bank versus comparably few broken polyethylene lines at Westham Island may indicate a large difference in the physical environments between the two sites (e.g., wind, wave, or tidal energy). The broken polyethylene lines at Sturgeon Bank may also be a product of the *Ulva spp*. bloom. We observed *Ulva spp*. accumulate on the polyethylene lines during the ebb tide from August-October 2016. It is plausible that the weight of the algae on the polyethylene lines during low tides and the increased drag force from *Ulva spp.* accumulating on the polyethylene lines during the draining ebb tide may have contributed to or caused the polyethylene lines to break at

Sturgeon Bank. Regardless of the cause, it is evident that there are strong physical forces acting at the Sturgeon Bank mud and sand flats (and perhaps also the marsh) that are not present at the same magnitude at the Westham Island marsh leading edge. It is possible these forces stress Sturgeon Bank marsh vegetation (Table 2.1.) and have contributed to the marsh recession (Fig. 2.2.; Marijnissen, 2017).

Regarding testing the elevation hypothesis, the assumption that plots at lower elevations at Sturgeon Bank would be inundated with water for longer periods may be an over-simplification of the water-exposure of transplanted rhizomes. Smaller sizes of sediment (e.g., mud) can retain water longer than larger grains (e.g., sand) during low tides (Mitsch and Gosselink, 2007), and sediment grain size appeared to vary between plots (i.e., fine sediments at the leading edge transitioning to coarse sediments at the *S. pungens* islands, generally), though I did not quantify this parameter. Additionally, I assigned Sturgeon Bank treatment plots at regular elevation intervals (i.e., every 0.31 m) from the average Sturgeon Bank marsh leading edge elevation. However, some treatment plots are adjacent to drainage channels, and thus may be exposed to water for longer periods of time during the ebb tide and greater quantities of *Ulva spp*. as the tide ebbs. To ensure that all three replicates for each treatment were exposed to the same conditions, it may have been wiser to have constructed each replicate 10 m apart from each other along one transect instead of constructing each treatment replicate along three transects spaced approximately 800 m apart (Fig. 3.5.). Lastly, much of the area between the remnant *S. pungens* islands and the marsh leading edge retains approximately 1-4 cm of water during the low tide (E. Balke 2016, personal observation). This poorly-drained shallow depression is likely caused by scouring around the sand swells that terminate at the *S. pungens* islands (Marijnissen, 2017). The greatest densities of non-native eelgrass, *Zostera japonica*, observed at Sturgeon Bank are in this area (E. Balke 2016, personal observation). The ability of eelgrass to survive in this area likely indicates the abiotic environment, specifically saturated sediments, is not appropriate for bulrush growth and may prevent *S. pungens* and/or *B. maritimus* from recolonizing this area of Sturgeon Bank. Thus, treatment plots K/J/I-1 and K/J/I-2 may be inundated for longer periods of time than expected with the experimental design.

Though the reciprocal transplant experiment involved transplanting *S. pungens*, the unexpected wide distribution of *B. maritimus* corms throughout the receded areas of marsh at Sturgeon Bank (Fig. 2.4.) may indicate that certain areas of the mud flats are inappropriate for *S. pungens* growth, and a large proportion of biomass lost from the recession is from the death of *B. maritimus*. *S. pungens* grows in well-drained, coarser substrates with relatively low moisture content in areas with greater fresh water influence, while *B. maritimus* grows in finer, more saline substrates with poor drainage and restricted fresh water influx (Hutchinson, 1982; Karagatzides, 1987; Karagatzides and Hutchinson, 1991). Based on my qualitative observations, the locations of treatment plots K/J/I-1 and K/J/I-2 have substrate conditions more suitable for *B. maritimus*, while the locations of all other plots are more suitable for *S. pungens*. Considering one of the goals of the reciprocal transplant experiment is to generate information needed to eventually revegetate the receded marsh at Sturgeon Bank, it would have been prudent to transplant *B. maritimus* in addition to *S. pungens*.

Annual preliminary data collection of transplanted *S. pungens* cores may adversely impact the experiment. We plan to measure shoot number and density of every transplant each June until termination of the experiment in 2019 to calculate preliminary survival and growth of transplants. However, measuring these metrics at plots with fine sediments (i.e., treatment plots K/J/I-1 and K/J/I-2) will require field technicians to walk throughout the treatment plots and disturb the muddy sediment surrounding the transplants. It may be less destructive to the transplants to visually count the number of shoots in each core in these treatments from outside the goose exclosures. Additionally, another large *Ulva* spp. bloom from May to August 2017 may occur and smother the stems of transplanted bulrush again. In this event, I recommend counting the number of new shoots at all experimental plots monthly from April to June.

3.3.2. Implications of Anticipated Results

3.3.2.1. Bulrush Salinity Tolerance Greenhouse Experiment

If transplanted cores survive the coring process and additional stressors of the experimental process (e.g., smothering by *Ulva spp*. and herbivory by geese) and the results of the reciprocal transplant experiment support the salinity hypothesis, the next step will be to conduct a bulrush salinity tolerance greenhouse experiment. Since we cannot isolate and manipulate salinity in a field experiment at the Sturgeon Bank and Westham Island marshes, the reciprocal transplant experiment contrasts the different growing environments of the two sites, of which salinity is a major component. Other likely differences between the two marshes include *Ulva* spp., goose herbivory, wind and wave energy, currents, and slough water input from dike-based pumping stations.

We plan to conduct a bulrush salinity-tolerance experiment to help interpret the reciprocal transplant experiment results. The goal of this experiment is to determine if there is a salinity threshold above which bulrush from the leading edge marshes grow poorly and die. We will expose *S. pungens* and *B. maritimus* nursery stock and cores harvested from Sturgeon Bank and Westham Island to varying levels of salinity over an entire growing season in a controlled greenhouse environment.

After collecting additional salinity data from the two field sites I am no longer confident we can mimic the dynamic salinity and tidal conditions to which bulrush are exposed at the leading edge marshes to a biologically relevant extent. Preliminary analysis of the salinity data from the water meters indicates that bulrush at Sturgeon Bank are exposed to highly variable levels of salinity between tide cycles and within a single tide cycle (B. Gurd 2017, unpublished data). For example, one water meter at Sturgeon Bank registered a practical salinity range of 0-20 within one tide cycle. Exposing bulrush to such a range of salinities daily over a five-month growing season in a controlled salinity tolerance lab experiment is unlikely to be feasible. Further, exposing bulrush to a single salinity of water for an entire growing season is not biologically relevant. It is also challenging to mimic a realistic tide cycle for *S. pungens*, which varies from being completely submerged to completely exposed. It may not be possible to conduct a biologically relevant bulrush salinity-tolerance greenhouse experiment as originally required to interpret the results of the reciprocal transplant experiment. Hutchinson (1988) documented large areas of *S. pungens – B. maritimus* communities in the Stillaguamish, Nooksack, Skagit, and Courtenay delta marshes; it may be valuable to monitor salinity levels at *S. pungens* low marsh monotypic stands at other estuaries throughout the Puget Trough to determine a range of salinities that *S. pungens* can tolerate.

3.3.2.2. Restoring Sturgeon Bank

It may be necessary to increase the flow of fresh water to the marsh if we eventually conclude that elevated salinity has contributed to the Sturgeon Bank marsh recession or presently prevents bulrush revegetation of the marsh. Pumping stations at the Sturgeon Bank dike enable controlled releases of ditch water from the adjacent city of Richmond. However, the quantity of fresh water released is likely insufficient to significantly change the salinity of water throughout the entire marsh during each flow tide. A more permanent and feasible solution may be to create additional gaps in the SNJ to allow more fresh water from the Main Arm of the Fraser River to continuously flow into the Sturgeon Bank mud and sand flats, similar to the Garry Point Slough at the southern extent of the marsh. This would be a complicated and expensive procedure that involves altering infrastructure.

Alternatively, if elevated salinity is the issue it may be necessary to restore the marsh using more salt-tolerant plant stock or species with a greater salinity tolerance. Even with its possible confounding factors and experimental design flaws, the reciprocal transplant experiment may still reveal the existence of *S. pungens* ecotypes that are better at surviving higher salinity brackish water. If *S. pungens* transplants survive very poorly at Sturgeon Bank, *S. pungens* may not be the ideal species to revegetate the marsh. Karagatzides (1987) notes that *B. maritimus* grows in more saline substrates further away from fresh water inputs compared to *S. pungens*. Thus, *B. maritimus* may be more appropriate for revegetating the marsh. The reciprocal transplant experiment may yet reveal that *S. pungens* nursery stock may be a viable method of revegetating Sturgeon Bank. However, considering that many *S. pungens* and *B. maritimus* plants have died off as part of the marsh recession (Section 2.1.1.), the task of restoring the Sturgeon Bank marsh will likely not be as straightforward as simply transplanting bulrush to areas of receded marsh; most likely, to some extent the physical environment must be ameliorated or altered in order for the marsh to regrow.

Interpreting the data from the reciprocal transplant experiment control plots may indicate that my method of coring significantly decreases growth and survivorship of transplanted cores. When standardizing the length of cores to 0.15 m we often cut off additional roots and rhizomes, which may have negatively impacted survival of each core. Boyd (1995) suggests that a reserve of deep (i.e., >0.20 m) *S. pungens* rhizomes may be important in maintaining bulrush growth when waterfowl grubbing intensity is high. Alternative methods of harvesting and planting *S. pungens* cores may enable better growth and survival of transplants, which may be important for revegetating large areas of Sturgeon Bank.

If transplants in treatment plots at greater elevations grow and survive better than those at lower elevations, it may be necessary to artificially elevate sections of the mud flat to revegetate the Sturgeon Bank marsh. The SBMRP has considered depositing dredge spoil from the Fraser River on the areas of receded marsh. However, modelling by Northwest Hydraulics Consultants (NHC) predicts that large 500,000 m^3 deposits of dredgeate on the Sturgeon Bank mud flats will not distribute evenly across the Bank but rather stay in place (NHC, unpublished data). Cost and logistical constraints aside, we do not know if vegetating the top of such dredge spoil "islands" is feasible or possible. The feasibility of creating dredge spoil marsh islands may be very important to explore further with a pilot project because of the anticipated rise in net relative sea-level in the Strait of Georgia (Kirwan and Murray, 2008; Hill, 2006 in Lemmen et al., 2008).

3.3.3. Conclusions

Several factors may confound the results of the reciprocal transplant experiment and the experimental design may be imperfect; however, these are valuable lessons that we only learnt as a product of conducting extensive field work at the Sturgeon Bank and Westham Island marshes. We now have a better understanding of the dynamic nature of the Sturgeon Bank marsh and factors that may prevent its recovery. The lessons of this pilot project and any data we collect from the experiment in upcoming growing seasons can influence future experiments and restoration efforts at Sturgeon Bank and the other leading edge brackish marshes of the Fraser River delta.

It may be naïve to attempt to understand the underlying cause(s) of the recession with short-term experiments considering that the Sturgeon Bank marsh recession likely occurred over a 20-30 year period. Ideally, we would understand and ameliorate the stressors causing the recession before attempting restoration. As that may not be possible, it is likely worthwhile to conduct adaptive management ecological restoration experiments (Holling, 1978; Walters and Holling, 1990) to determine optimal designs for a restoration prescription. The anticipated effects of sea-level rise and climate change cannot be ignored and must be taken into account in the restoration and management of the Sturgeon Bank marsh. In Chapter 4, I provide recommendations for researching, monitoring, managing, restoring, and working at the foreshore brackish marshes of the Fraser River delta.

Chapter 4.
Recommendations

> *A key to advancing the state of knowledge concerning the development of estuarine marsh ecosystems lies in never losing sight of the big picture, and the implausibility of isolating individual components out of a natural continuum.*
>
> (Luternauer et al., 1995)

4.1. Prioritizing Research and Hypotheses to Test

As Marijnissen (2017) suggests, the SBMRP Working Group needs an integrated approach to investigating the Sturgeon Bank marsh recession. It is difficult to evaluate which processes caused the recession because we do not fully understand the complex interaction between these processes. Thus, there are many remaining avenues of inquiry to pursue in advance of attempting to restore the Sturgeon Bank marsh. We can better understand what marsh has been lost and what is presently in those areas of receded marsh. In designing pilot projects to investigate additional recession mechanisms, we need to focus on the physiological mechanisms of plant death and the environmental conditions in specific areas of Sturgeon Bank that allow low marsh plants to persist. The Sturgeon Bank marsh is not the only leading edge marsh in the Fraser River delta that has receded, thus the scope of the investigation should be widened. There are also plenty of opportunities to collaborate with researchers in other specialties and jurisdictions, particularly to understand the 2016 bloom of *Ulva* spp. and its potential negative impact on the brackish marshes.

I suggest conducting a systematic survey of *B. maritimus* corms across the Sturgeon Bank flats and collecting data on additional environmental parameters to help us better understand what marsh vegetation has receded and the conditions in these areas of receded marsh. For the corm survey I conducted (Section 2.1.1.; Fig. 2.4.) I used a non-standardized, non-systematic method to find the lowest elevation at which I could find corms. It would be useful to repeat this survey across several dozen transects across the entire area of receded marsh at Sturgeon Bank. This will give us a better picture of the historical marsh composition and extent to which *B. maritimus* has receded compared to *S. pungens*. During my original survey I found *B. maritimus* corms at the sediment surface and at different depths below the surface of the flats. This may indicate that at certain areas of the former marsh sediments eroded, while at other areas sediments accreted. A full site survey should measure precise depth and number of corms. Lead-210 dating sediment surrounding corms at different depths may provide insight into the history of sediment accretion/erosion and marsh recession/expansion over the decades that historic air photos and previous studies cannot provide. Analysis of pore water salinity, grain size, and organic content of sediment samples with corms will also help us understand the environmental conditions of receded areas of marsh that are not conducive to bulrush growth. Non-native *Z. japonica* eelgrass grows in many areas of former marsh. Measurements of *Z. japonica* density and distribution throughout Sturgeon Bank should be collected during the corm survey because these parameters have not yet been comprehensively measured. We should also dig several pits through the remnant *S. pungens* islands to determine the depth of *B. maritimus* corms and if there is a lens of mud underneath the sand swells. These data may indicate a previous *B. maritimus* community was covered over by sand as the sand swells moved northeast (S. Boyd 2017, personal communication).

To investigate additional recession hypotheses, we need to continue focusing on the plants that have died: what are physiological mechanisms for plant death and what ongoing conditions have allowed *S. pungens* and *B. maritimus* to persist in specific areas of Sturgeon Bank? Hutchinson (1982) describes how the elevation – salinity – sediment water content interaction is very marked in both species of bulrush. As major determinants in the distribution of *S. pungens* and *B. maritimus*, we should look for locations at Sturgeon Bank where these conditions have shifted. At the south of Sturgeon Bank there are a series of three large radio towers connected by a pier projecting into the marsh (Fig. 2.6.). Satellite imagery (Google, 2017) reveals that since 2004 the marsh has receded approximately 100 m shoreward of the pier terminus; however, there is still *B. maritimus* and some *S. pungens* growing underneath the pier (E. Balke 2017, personal observation). It would be valuable to analyze this area in greater detail to identify why bulrush was able to persist (e.g., shading or wave energy barrier). Based on these findings, we can design pilot projects in which we transplant bulrush into plots where these factors are manipulated (e.g., anchoring a LWD wave energy barrier seaward of a transplant plot). The *S. pungens* islands are in another area of remnant low marsh that has survived. These patches of vegetation may have survived because they grow on sandy, well-drained substrate. It may be worthwhile to transplant *S. pungens* and *B. maritimus* on top of deposited mounds of sediment, each mound with a different sediment particle size (i.e., sand, silt, or mud). Any future transplant experiments should include both *S. pungens* and *B. maritimus* since the Sturgeon Bank recession involves these two species. In the reciprocal transplant experiment I planted cores one metre apart from each other; any further transplanting should plant bulrush at different densities to see if this increases the success rate of transplanted bulrush.

The scope of the recession investigation should be widened because Sturgeon Bank foreshore brackish marsh is not the only foreshore marsh of the Fraser River delta that has receded. Hales (2000) first described the marsh recession at Sea Island almost two decades ago and Boyd (unpublished data) has stem density data from 1989 to present showing marsh recession at Westham Island and Brunswick Point from his long-term *S. pungens* bulrush monitoring plots. Though it is possible the loss of marsh at all four locations was not caused by the same mechanism(s), it is highly unlikely that these four recession events are completely independent, considering it appears each marsh has receded since 1989. From my coarse interpretation of satellite imagery (Google, 2017), it appears that the marsh recessions at Sturgeon Bank, Sea Island, and Brunswick Point have stabilized; however, as confirmed by S. Boyd (unpublished data) and B. Mason (unpublished data), the Westham Island marsh continues to recede. It would be valuable to survey areas of receded marsh at each of the four sites to compare physiologically relevant parameters for *S. pungens* and *B. maritimus* growth (e.g., salinity, inundation time, sediment size, and sediment organic content) in order to formulate hypotheses for marsh recession shared between multiple sites. It may also be useful to conduct a systematic *B. maritimus* corm survey at each of the brackish marshes, not just the Sturgeon Bank marsh, to better understand the type of marsh that receded at each location. Considering the scale at which some of the proposed mechanisms for marsh recession act (e.g., sea-level rise and elevated salinity), it is unlikely that all three other foreshore brackish marshes would not also be affected by the stressor(s) that caused the Sturgeon Bank marsh recession.

The SBMRP is an excellent opportunity to collaborate with researchers from other disciplines who may view the marsh recession from a different perspective. For example, we have made no attempt to investigate the impact of the recession on the invertebrate community and the detrital food web though Levings (1980) previously studied the consequences of training walls and jetties for aquatic habitats at Sturgeon Bank. We also have not quantified the impacts of the marsh recession on carbon accumulation and methane budgets. Perhaps the area of research that requires the greatest amount of collaboration and further study is the *Ulva* spp. bloom of 2016. It is worth studying the effect of algae coverage and subsequent anoxic conditions on marsh growth and survival at the leading edge marshes at Sturgeon Bank and Sea Island. These so-called “green tide” algal blooms have become prominent along the coast of the Pacific Northwest (Nelson et al., 2003) and around the world (Ye et al., 2011). Researchers have evaluated the impacts of these green tides on eelgrass and other ecosystems (Bittick et al., in review; Van Alstyne et al., 2015; van Hulzen et al., 2006; Nelson and Lee, 2001). Temperature and nutrients can be limiting factors for *Ulva* spp. blooms; however, many of these blooms occur in relatively pristine waters and show no influence from pollution or other human activities (Ye et al., 2011). We need to understand the local limiting factors for *Ulva* spp. in the Strait of Georgia and Fraser River delta to determine if the bloom in 2016 was a stand-alone event or if future blooms are likely, especially with the new environmental paradigm predicted as a result of climate change and sea-level rise. Frequent *Ulva* spp. blooms may hinder or entirely prevent future restoration of the low marsh at Sturgeon Bank.

4.2. Monitoring and Maintaining the Foreshore Brackish Marshes

It is often easier and more cost-effective to maintain an existing ecosystem than it is to restore a degraded ecosystem (Rieger et al., 2014). One hundred and sixty hectares of highly productive estuarine marsh died at Sturgeon Bank from 1989 to 2011 without anybody noticing. It is important that the estuary does not succumb to shifting baselines syndrome (Pauly, 1995) where the extent of ecosystem loss is unknown due to sparse baseline data. The first step to maintaining and protecting the foreshore brackish marshes of the Fraser River delta is to monitor these wetlands so that we (a) know what ecosystems presently exist, (b) understand what ecosystems have disappeared, and (c) better inform and equip decision makers to proactively respond to ecological degradation.

4.2.1. Brackish Marsh Recessions

All efforts to track marsh recession to date have compared the relative location of the marsh leading edge between different dates (i.e., tracking the location of the marsh leading edge as it retreated shoreward). Marijnissen (2017) notes that the Sturgeon Bank marsh leading edge remained relatively stable from the 1930’s to early 1980’s, leading him to conclude that the marsh was not receding over this period. It is possible that the marsh vegetation communities changed over that 50-year period (e.g., different communities, species, or stem densities), though no data has been collected to test this hypothesis. Marsh community change may be a precursor to marsh recession. For example, while monitoring the loss of marsh at Westham Island since 1989, Boyd (unpublished data) observed that a decrease in *S. pungens* stem density preceded conversion of a large area of low marsh into an unvegetated mud flat. I recommend conducting a comprehensive vegetation survey of the Sturgeon Bank marsh for comparison to Hutchinson (1982) and Boyd (1983). The SBMRP has exclusively focused on the low marsh, however it is possible that the middle and high marshes have also degraded. Digital analysis of modern satellite and drone imagery enables more precise and efficient mapping of marsh communities when combined with on-the-ground GPS surveys of vegetation community boundaries.

The scope of monitoring marsh integrity should not be limited to the Sturgeon Bank marsh. Full-marsh vegetation surveys should be conducted at all four foreshore brackish marshes of the Fraser River delta and compared to previous surveys (e.g., Burgess, 1970; Yamanaka, 1975) to track each marsh recession. Boyd fortuitously established his long-term bulrush monitoring plots at the Westham Island low marsh before that marsh started receding. We should look to this as an example of the value of long-term monitoring plots. There are many other ecologically important areas and functions throughout the Fraser River delta Wildlife Management Area that should be regularly monitored. These areas include native eelgrass (*Z. marina*, common eelgrass) beds off Sturgeon Bank, Roberts Bank, and Boundary Bay; biofilm at Roberts Bank; salt marshes at Roberts Bank and Boundary Bay; and the South Arm Marshes.

4.2.2. Elevation and Substrate

The presence of several major infrastructure works throughout Sturgeon Bank and Roberts Bank merit regular monitoring of the substrate of the Banks. Elevation and sediment size are important determinants of marsh vegetation zonation in the low marsh, as discussed in Section 2.1.1. The Iona North Jetty, Iona South Jetty, Steveston North Jetty, Roberts Bank Causeway, and Tsawwassen Ferry Terminal Causeway each modify the movement and transport of water and sediments across the foreshore of the Fraser River delta. These infrastructure works may decrease the supply of sediment to the foreshore brackish marshes, and thus impair the marsh surface from maintaining equilibrium with local sea-level rise (Weinstein et al., 2001). Not only may the decreased mobility of sediments across the delta front impair marsh development, but this change in sediment mobility may also expose protective dike infrastructure to additional wave energy over the coming decades of sea-level rise. Annually-collected high-resolution lidar may be the most comprehensive way to accurately monitor sediment changes across Sturgeon and Roberts Bank. However, to compare multiple lidar surveys we will need to collect these data at the same time of year. Boyd (unpublished data) observed regular seasonal variation in substrate elevation at the *S. pungens* low marsh at Westham Island; from 1990-1994, the marsh surface was 3-6 cm higher in the summer relative to the winter.

4.2.3. Algae

To begin understanding the impact of algae blooms on the foreshore marshes we first need to identify which species of algae are present. Sea lettuce smothers the Sturgeon Bank and Sea Island marsh (E. Balke 2016, personal observation), an unknown filamentous algae may contribute to marsh loss at Westham Island (S. Boyd 2016, personal communication), and *Ulva* hummocks and mats accumulate on mud flats south of Canoe Pass (Hemmera, 2004). Once we identify each species of algae we may identify factors that determine their growth and different distributions throughout the Fraser River delta.

After distinguishing algae species present, we should begin to monitor the accumulation, distribution, and transport of *Ulva* spp. throughout the Fraser River delta foreshore marshes and flats. I used wooden stakes to mark the perimeter of an approximately 250 m^2 accumulation of *Ulva* spp. along the leading edge of the middle marsh at Sturgeon Bank in August 2016. By the next day, the algal accumulation had shifted 0 to 5 m, and nine days later most of the accumulation had disappeared entirely (Fig. 4.1.). It appears that *Ulva* spp. accumulations on the Sturgeon Bank marsh and mud flat shift daily, though some areas were more frequently smothered throughout the summer of 2016. To understand which areas of Sturgeon Bank are frequently smothered by algae, we need to use repeated satellite or aerial imagery. Only by analyzing the daily changes in algal smothering can we determine where and to what extent the marsh is potentially adversely impacted. Frequent monitoring will also allow us to discern any seasonal or annual patterns and variation in *Ulva* spp. accumulation throughout the Fraser River delta foreshore brackish marshes. We can also extend this monitoring to the inter-causeway area, Tsawwassen beaches, Boundary Bay, and south coast of Point Grey to get a more complete picture of the *Ulva* spp. distribution and accumulation around the Fraser River delta.

Figure 4.1. Photos of the Sturgeon Bank middle marsh with accumulation of *Ulva* spp. algae (left, 20 August 2016) and without *Ulva* spp. 10 days later (right, 30 August 2016). Photos by E. Balke.

4.2.4. Invasive Species

The Sturgeon Bank brackish marsh and other marshes in the Fraser River estuary are further threatened by the establishment of invasive species. Non-native eelgrass colonization of receded areas of the Sturgeon Bank marsh may not be as innocuous as previously thought. *Z. japonica* is often not considered an invasive species, though it is widely spread throughout many intertidal zones along the Pacific Northwest coast (Kaldy, 2006; Posey, 1988). Some researchers argue that this non-native eelgrass does not compete with native *Z. marina* due to *Z. japonica*'s smaller size and, because of its smaller morphology, *Z. japonica* occupies higher intertidal elevations and can better tolerate exposure than the native eelgrass (PIBC, 2002). However, other researchers consider *Z. japonica* invasive because (1) competition with *Z. marina* reduces the native eelgrass' performance (Bando, 2006) and (2) *Z. japonica* it is an ecosystem engineer (Sutherland et al., 2013; Tsai et al., 2010; Hahn, 2003; Larned, 2003). *Z. japonica* reduces water flow by up to 40% and retains water at low tide compared to unvegetated intertidal flats; this creates a positive feedback in which *Z. japonica* engineers its environment to enable greater growth despite lengthy low tides (Tsai et al., 2010). Mean sediment grain size declines, sediment volatile organics increases, and faunal richness increases in patches of intertidal flats with *Z. japonica* in the Coos Bay estuary (Posey, 1988). *Z. japonica* also alters microbial community composition (Hahn, 2003) and water column benthos nutrient fluxes (Larned, 2003) in other Pacific Northwest estuaries. As an ecosystem engineer, it is plausible that *Z. japonica* colonization of receded areas of the Sturgeon Bank marsh may prevent recolonization by *S. pungens* and *B. maritimus* by promoting conditions not conducive to bulrush growth. It is therefore prudent to comprehensively survey the density and distribution of *Z. japonica* at the Sturgeon Bank flats to begin to investigate possible impacts on recolonization and revegetation of native marsh plants.

Invasive *Spartina anglica* (English cordgrass) poses an immediate threat to the delta front brackish marshes. *S. anglica* spread north to Boundary Bay in 2003 after being introduced to Puget Sound in 1961 for dike and shoreline stabilization. *S. anglica* is a highly invasive cordgrass that rapidly colonizes coastal marshes and converts mud flats to monotypic stands, accretes sediments, and modifies drainage patterns resulting in a loss of productive ecosystems used by fish and waterfowl. *S. anglica* remains ubiquitous throughout Boundary Bay and Roberts Bank south of Canoe Pass despite active eradication efforts (DUC, 2015; Williams et al., 2009). A single *S. anglica* clone was found in the *Z. japonica*-dominated area at Sturgeon Bank in August 2016 (E. Balke 2016, personal observation); *S. anglica* had never been observed north of Canoe Pass prior to this observation (DUC, 2015; Williams et al., 2009). It is likely that this invasive plant will continue to colonize the marsh and flats throughout Sturgeon Bank if control measures for *S. anglica* do not limit its continued northward expansion. Remnant marsh and any restored or revegetated marsh at Sturgeon Bank may be outcompeted for important resources by *S. anglica*. It is crucial to continue annual surveys along the Metro Vancouver coastline to exterminate lone clones and small patches of *S. anglica* before it becomes established. It is particularly important to survey the Sturgeon Bank flats for this invasive species because it is likely capable of rapidly colonizing receded areas of the Sturgeon Bank marsh, and thus hindering any revegetation or restoration of the marsh with *S. pungens* and *B. maritimus*. *S. anglica* has at least five identified mechanisms by which it tolerates saline water (Thompson, 1991); it is likely that *S. anglica* can tolerate the elevated salinity at the Sturgeon Bank low marsh considering it is widely distributed across the highly saline waters of Boundary Bay.

A hybrid race of non-migratory Canada geese threatens the marshes of the Fraser River estuary. Dawe and Stewart (2010) chronicle the government-led introduction of non-native subspecies of Canada geese from 1918 through the 1980’s to provide hunters with a harvestable surplus and increase wildlife viewing opportunities throughout the BC Lower Mainland and southern Vancouver Island. Interbreeding resulted in an abundance of resident hybrids of at least three subspecies that have caused significant ecological damage to estuarine marshes due to intense herbivory (Dawe et al., 2011). Dawe and Stewart (2010) suggest that the resident Canada goose hybrid race should be considered an exotic, invasive species and managed accordingly because of these negative ecological impacts and the historical rarity of resident Canada geese in the area. Intense, year-round grazing pressure from resident Canada geese may prevent natural recovery of receded and degraded marshes throughout the Fraser River delta. Canada goose grazing significantly reduced the fitness of grazed *C. lyngbyei* plants during restoration of a heavily urbanized estuary in Washington State (Simenstad et al., 2005). Grazing pressure from waterfowl is the leading hypothesis to explain the loss of high elevation low marsh at Westham Island (S. Boyd 2016, personal communication).

Increasing numbers of Canada geese and snow geese, along with the decreasing quantity of remnant marsh throughout the Fraser River estuary, likely results in greater grazing pressure on the remaining marshes. In 1974/1975, approximately 15,000 snow geese removed one-third of the below-ground biomass of bulrush in the Fraser River estuary (Burton, 1977). Approximately 100,000 snow geese returned to the

Fraser and Skagit River estuaries in the winter/spring of 2016/2017 (S. Boyd 2017, personal communication), in addition to an unknown number of invasive resident Canada geese. Using simulation modelling, Demarchi (2006) predicts that – without factoring the loss of the majority of the Sturgeon Bank low marsh – the brackish marshes of the Fraser River delta in 2006 were capable of supporting herbivory by approximately 17,500 migratory snow geese. The Delta Farmland and Wildlife Trust has helped farmers in the lower Fraser River delta establish live winter cover crops on their fields for the last 25 years to, in part, provide food for waterfowl and migratory shorebirds and effectively supplement marsh vegetation herbivory (Odhiambo et al., 2012).

Local governments should consider initiating a coordinated Canada goose management program in order to prevent further degradation of the Fraser River delta marshes. Feasible control measures include egg addling and promoting hunting and culling of Canada geese throughout the lower Fraser Valley. For example, in 2016 the city of Parksville, BC captured and culled 484 resident Canada geese during moulting in the Englishman River estuary, and members of the K'omoks First Nation harvested some of the meat. This cull cost approximately $72 per goose, which was one-tenth the cost of a similar 2015 cull in Victoria, BC (Rardon, 2016). Implementation of goose population control measures may face public opposition, therefore partnering with all levels of government (including First Nations) and initiating outreach programs may be necessary to educate the public about this ecological calamity.

4.3. Restoration

It is prudent to refrain from commencing large-scale marsh restoration or creation efforts at the Sturgeon Bank marsh prior to better understanding the underlying mechanism(s) of marsh recession. Restoration of degraded ecosystems should not be seen as a replacement to ongoing monitoring, maintenance, and protection of existing ecosystems.

Weinstein et al. (2001) identify seven crucial factors favouring successful wetland restoration (Table 4.1.) as a result of completing one of the world's largest tidal marsh restoration projects. Any marsh restoration or creation projects should use an adaptive management design (Holling, 1978; Walters and Holling, 1990) that enables us to learn about the system and determine the most effective restoration prescriptions. Keeping in

Table 4.1. Physical, chemical, and biological factors favouring successful wetland restoration (Weinstein et al., 2001).

Factors Favouring Successful Wetland Restoration
1) Historical ecosystem types: ecosystems that were historically present at the site indicate potential suitability for re-establishing a similar ecosystem
2) Hydrology and topography: wetlands require a certain level of inundation and water flow
3) Creeks and channels: allows marsh to flood and drain with wetting/drying cycles long enough to aerate surfae sediments by drainage or evapotranspiration
4) Sediment organic content: supports active nutrient cycling and energy flow processes
5) Colonizer presence and proximity: adjacent wetlands provide a source of propagules and colonists to help achieve rapid invasion of appropriate organisms
6) Salinity: plays a large role in determining vegetation and faunal communities of salt/brackish marshes
7) Sediment accretion: constant supply of sediment maintains marsh surface in equilibrium with local sea level rise

mind the sheer size of the receded marsh, a feasible manner by which we may conduct such experiments is through small-scale pilot projects with dual goals of revegetating the marsh and identifying likely recession mechanisms (Section 4.1.; Marijnissen, 2017).

Restored, enhanced, and created marshes in the Fraser River estuary have a very low success rate. Lievesley et al. (2017) estimate that only one-third of marsh compensation sites created throughout the Fraser River estuary from 1983 to 2010 are acceptably compensating for fish habitat loss as required by the Fisheries Act (RSC 1985, c. F-14). Given the limited success of compensation efforts throughout the Fraser River estuary, in order to maximize the ecological functions and services that these marshes provide, it is important to minimize the destruction of Fraser River tidal marshes rather than assuming habitat compensation can effectively offset damage to these ecosystems.

According to Fisheries and Oceans Canada (DFO), the Sturgeon Bank low marsh is a high value ecosystem for fish and wildlife and should be prioritized for restoration. The Vancouver Fraser Port Authority (VFPA) signed a 5-year agreement with DFO in 2012 to develop and operate a habitat bank to credit the creation and enhancement of fish habitat against future VFPA or waterfront development projects requiring habitat compensation (VFPA and DFO, 2012). The agreement emphasizes creation of so-called “high value” habitat types that support a large number of ecological services and species functions (e.g., eelgrass beds and low marshes) to increase fish productivity (VFPA and DFO, 2012). However, not all compensation projects completed under this agreement prioritize creating, enhancing, or restoring high value fish habitat types such as the Sturgeon Bank low marsh. The VFPA’s Habitat Enhancement Program removed dense accumulations of woody debris and litter that smothered 8.22 ha of high elevation salt marshes and installed wildlife snags at five sites in Boundary Bay and Roberts Bank in 2013 (VFPA, 2014a; 2014b; 2014c). The DFO credited the Habitat Banking Credits at 95% of the restored log covered area (DFO, 2013a). Possession of these Credits enables the VFPA to withdraw approximately 7.81 ha from the habitat bank to offset the destruction of high value eelgrass beds as a result of the possible future expansion of Terminal 2 at Roberts Bank. High elevation salt marshes do not have equal functional values for fish relative to eelgrass beds (Short et al., 2000), therefore enhancing salt marshes to offset destruction of eelgrass beds does not appear to maintain or enhance the ongoing productivity and sustainability of commercial, recreational, and Aboriginal fisheries as required by federal law (DFO, 2013b; Fisheries Act, RSC 1985, c. F-14). As per their agreement, DFO and VFPA should prioritize the restoration of high value ecosystems analogous to those degraded by industrialization throughout the estuary. Furthermore, no party is mandated to restore or enhance intertidal marshes in the Fraser River delta that have slowly degraded, such as the Sturgeon Bank marsh. If many parties collectively benefit from using the Fraser River estuary and likely contribute to its degradation, it seems appropriate that they should contribute to its stewardship and maintenance.

Protecting and maintaining existing ecosystems should be prioritized over restoring or enhancing degraded ecosystems (Rieger et al., 2014). If maintaining ecosystems is not possible, then it is of greater ecological value to restore degraded sites rather than create new ecosystems (Weinstein et al., 2001). Creating wetlands where none previously existed is a difficult process requiring elaborate construction efforts with success rates much lower than that of restoring degraded sites (Weinstein et al., 2001). The Habitat Enhancement Program has proposed to deposit dredge spoil from the Fraser River on the north side of the SNJ to create 43 ha of intertidal brackish marsh where none previously existed (Fig. 4.2.). Though the successful creation of additional marsh at this location would likely have ecological benefits, the project may have adverse impacts on Sturgeon Bank and our capability to restore the foreshore marsh. For example, Marijnissen (2017) suggests that wind and waves reflect off the SNJ and may push the sand swells toward the marsh. The VFPA plans to build a marsh along the location of this reflection. Creating marsh in this location may absorb energy from wind and waves and alter the reflection of this energy off the jetty, possibly changing the shoreward movement of the sand swells and other sediment. Creating marsh at this location may also limit the options for opening additional gaps in the jetty to

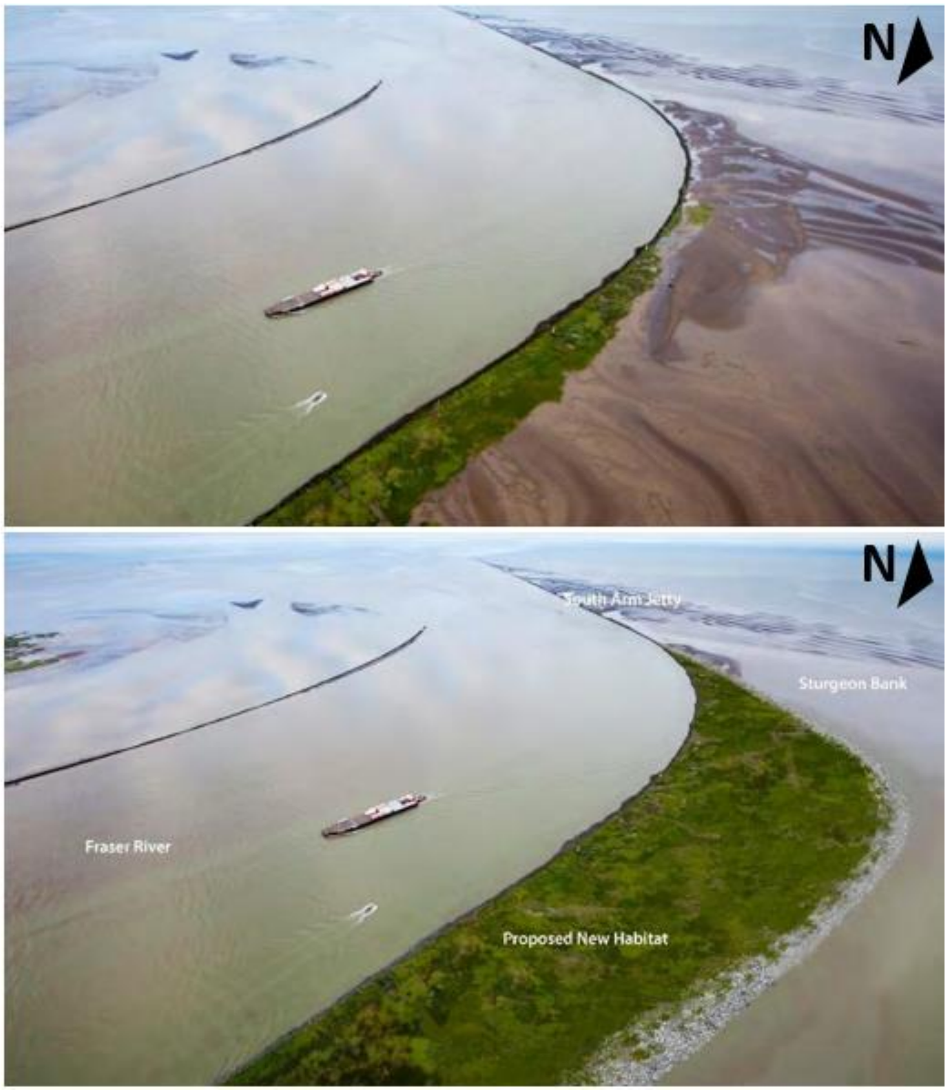

Figure 4.2. Pictures of the Habitat Enhancement Program's proposed marsh creation project immediately north of the SNJ at the Steveston Bend before (top) and after (bottom) project completion. Photos from the Vancouver Fraser Port Authority.

enable increased fresh water flow to the Sturgeon Bank marsh and flats. If elevated salinity has contributed to the Sturgeon Bank marsh recession, it may be worthwhile to design the VFPA marsh creation project to incorporate additional gaps in the jetty.

4.3.1. Factoring in Future Stressors

It is short-sighted to attempt to restore any ecosystem without factoring in future stressors; the brackish marsh at Sturgeon Bank is no exception. The estuary will continue to be developed for commercial, industrial, agricultural, and urban use, and any attempt to restore the foreshore marshes must take this into account. The VFPA has proposed the Roberts Bank Terminal 2 Project, a new three-berth container terminal at the Deltaport causeway on Roberts Bank. The project is presently undergoing a federal environmental assessment to evaluate and minimize the project's impact on fish, wildlife, and surrounding ecosystems. The BC provincial government is in the beginning stages of constructing the Massey Tunnel Replacement Bridge that would enable the province to remove the Massey Tunnel; the VFPA could then increase the depth of the Main Arm to enable passage of larger tanker traffic up to Annacis Island, the Fraser Surrey Docks, and New Westminster. There is also a proposal to expand YVR airport with the construction of a third runway across the Sea Island marsh and mud flat. Each of these large projects may (1) alter the delivery of water and sediments to the foreshore brackish marshes of the Fraser River delta and (2) result in serious harm to fish and waterfowl habitat, and thus require compensation under federal law. Further degradation of the intertidal marshes of the Fraser River delta may put more demand on remnant marshes, particularly when unexpectedly large numbers of snow geese return (as in 2016; S. Boyd 2017, personal communication) and non-migratory hybrid Canada geese populations are not managed. However, over the twenty-first century all of the Fraser River delta marshes may be influenced more by the effects of climate change and sea-level rise.

4.3.1.1. Climate Change

The effects of climate change are already evident in every region of Canada (Lemmen et al., 2008) and the Fraser River basin is no exception. Climate change is anticipated to continue to influence the Fraser River watershed and likely alter the flow of the Fraser River over the next century. The Fraser River watershed is a snowmelt-dominated basin throughout which it is expected the proportion of winter precipitation falling as rain will increase. This is anticipated to reduce the accumulation of winter snowpack and cause an earlier melt of a smaller snowpack resulting in a reduction in volume of spring freshet. An anticipated modest increase in winter precipitation throughout the watershed may increase winter snow accumulation and offset the anticipated impacts of warming (NHC, 2008).

Morrison, Quick, and Foreman (2002) created a flow model to project Fraser River flow and temperature changes over the next 85 years. The flow model predicts a 5% (i.e., 150 m^3/s) average flow increase of the Fraser River and a decrease in average peak flow during freshet of 18% (i.e., 1,600 m^3/s) from 2070-2099. They project these peaks would occur approximately 24 days earlier in the year though 13% of the time peak flow would occur later in the year as a result of summer and fall precipitation. The model predicts an increase of 1.9 °C in summer mean water temperature and the potential exposure of Pacific salmon to water temperatures greater than 20 °C (which likely degrades spawning success) is predicted to increase.

These predicted changes to the annual Fraser River spring freshet may adversely impact growth of the leading edge brackish marshes. The Fraser River foreshore brackish marshes experience their lowest salinities in the late spring and early summer; the annual freshet peaks during the growing season of marsh vegetation and this salinity minimum likely influences the timing of marsh growth (Hutchinson, 1982). If, as Morrison, Quick, and Foreman (2002) predict, the Fraser River decreases in average maximum flow and increases in average minimum flow, the amount of time during which salinity on the delta is reduced may increase. It remains unknown if this reduction in time that bulrush are exposed to higher salinity water is large enough to affect marsh vegetation growth rates (B. Gurd 2017, personal communication).

The 2016 Fraser River freshet was relatively low (Fig. 4.3.) and may have been a product of the accumulated effects of climate change throughout the Fraser River watershed. The 2016 Fraser River annual maximum flow at the hydrometric station at Hope, BC was the fourth lowest recorded since 1941 (i.e., maximum annual flow was 5,130 m^3/s in 1941, 5,950 m^3/s in 2010, 6,060 m^3/s in 1944, 6,070 m^3/s in 1980, and 6,130 m^3/s in 2016) (WSC, 2017). If salinity is one of the limiting factors of *Ulva spp.* growth, the low 2016 freshet may have resulted in higher-than-normal salinity in the

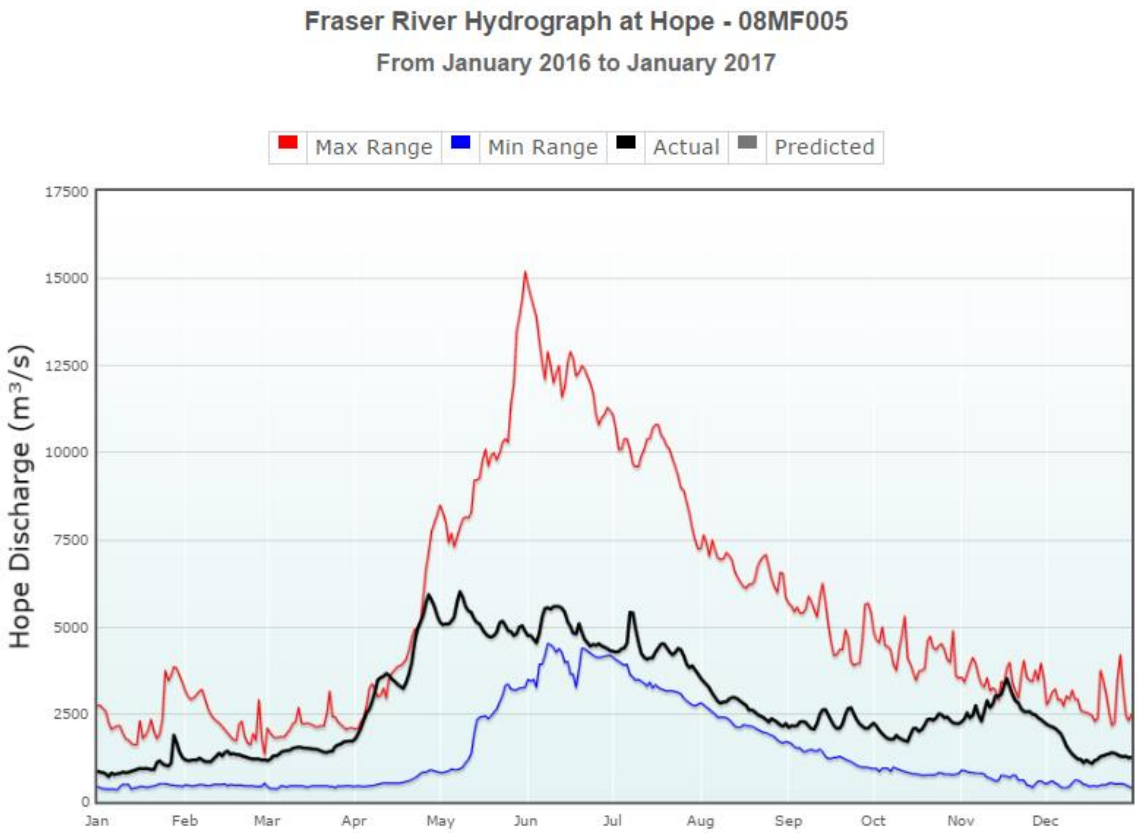

Figure 4.3. Fraser River hydrograph at Hope. The hydrograph includes the actual discharge of the Fraser River at the Hope monitoring station 08MF005 (black line), maximum range of discharge (red line), and minimum range of river discharge (blue line) since installation of monitoring station in 1912. Figure adapted from DFO (2017).

Strait of Georgia and stimulated the uncharacteristically large *Ulva spp*. bloom observed in the summer of 2016.

Climate change may also influence weather patterns in the Strait of Georgia that adversely affect the foreshore marshes. The Sturgeon Bank marsh has a high exposure (i.e., fetch) to westerly and northwesterly storm winds from the Strait of Georgia. Almost 50% of all wind speeds greater than 36 km/h at YVR airport on Sea Island came from the west to northwest between 1992 and 2012. Most waves are locally generated by winds, therefore Marijnissen (2017) concludes that waves arrive at Sturgeon Bank from the same direction as at YVR airport. However, the position of the Iona Jetty may influence the wave energy at the Sea Island foreshore greater than at the Lulu Island foreshore. If the effects of climate change were to increase the frequency and magnitude of winds in the Strait of Georgia, it is likely that the Sturgeon Bank foreshore marshes would be exposed to additional wave energy that may stress the marsh vegetation and affect sediment deposition and erosion dynamics.

The remaining Sturgeon Bank marsh communities may not be resilient to these conditions, and any restoration plan must account for the implications of climate change. Future conditions may not permit low marsh species, such as *S. pungens* and *B. maritimus*, to persist (Kirwan and Murray, 2008).

4.3.1.2. Sea-Level Rise

Sea-level rise over the next century may render all tidal marsh restoration efforts within the Fraser River delta futile. Factoring in climate change projections, the historical rate of relative sea-level rise from tide-gauge data, and new ground subsidence data, net sea-level is projected to rise 0.23 to 1.02 m at Roberts Bank by 2100 (Kirwan and Murray, 2008; Hill, 2006 in Lemmen et al., 2008). Both Roberts Bank and Sturgeon Bank consist of tidal flats with distinct ecological zones (i.e., eelgrass beds, sand/mud flats, and low/middle/high marshes) that tend to migrate inland in response to rising sea-levels. The presence of dikes impedes natural migration of these ecological zones shoreward with sea-level rise, and thus effectively squeezes these zones against the dikes (Hill, 2006 in Lemmen et al., 2008). Kirwan and Murray (2008) estimate this will result in a loss of 6-36% of the vegetated area of the Westham Island marsh. Though sea-level rise models produce a range of estimates for the magnitude of increase in mean sea-level, it is highly probable that the leading edge brackish marshes of the Fraser River delta will be adversely affected.

With this in mind, we must ask ourselves if it is worthwhile to invest the time and money restoring an ecosystem for which all restoration efforts may be completely submerged within 80 years. The SNJ probably decreases sediment accretion at Sturgeon Bank (Marijnissen, 2017; Williams and Hamilton, 1995; Milliman, 1980); thus, sediment deposition from the Fraser River may not be capable of offsetting the rise in sea-level. It may be necessary to elevate the marsh by depositing dredge spoil from the Fraser River throughout Sturgeon Bank. Given the physical constraints of pumping sediment long distances from a dredge ship in the Main Arm to the Sturgeon Bank flats and marsh, depositing dredge spoil throughout the Bank may be very expensive and logistically complicated. The Corporation of Delta is presently considering depositing large amounts of sediment in Boundary Bay to build up the sand flats, salt marsh, and dikes to protect the shoreline from sea-level rise. Though depositing large amounts of dredge spoil on the Sturgeon Bank marsh will smother vegetation, this may be the best option to protect the shoreline and enable the marsh to persist in the twenty-second century. Any measures taken to protect the shoreline from rising sea-levels (e.g., elevating the Iona Island Wastewater Treatment Plant or raising the dike at Lulu Island, Sea Island, or Westham Island) should be combined with efforts to increase marsh resilience to sea-level rise. In anticipation of this necessity, it would be prudent to experiment with depositing Fraser River dredge spoil throughout areas of receded marsh at Sturgeon Bank and planting with tidal marsh vegetation.

It may not be feasible to deposit sufficient amounts of dredge spoil to elevate the Sturgeon Bank flats and marsh given the prodigious challenge and cost. A cost-effective alternative may be to construct additional river training structures to promote sedimentation and marsh growth in areas of the delta front not used by commercial boats. Hales (2000) deduces that construction of the South Jetties from 1930-1954 increased sedimentation and marsh expansion south of the Main Arm and northwest of Westham Island. Construction of additional training walls designed to slow water flow and deposit sediments on the mud flats adjacent to the Westham Island and Brunswick Point foreshore marshes may facilitate the creation of additional marsh islands. Adding similar structures to the Sturgeon Bank flats may not have the same effect because the flats and marsh do not appear to be increasing in elevation (Marijnissen, 2017) perhaps because of a lack of accreting sediments (Marijnissen, 2017; Williams and Hamilton, 1995; Milliman, 1980). The predicted effects of sea-level rise may cause us to completely rethink options for restoring the Sturgeon Bank marsh and maintaining all foreshore marshes of the Fraser River delta.

Chapter 5.
Summary and Conclusions

The foreshore brackish marshes of the Fraser River delta front are extremely productive ecosystems that form an important part of the detrital food chain that includes Pacific salmon and waterfowl (Schaefer, 2004). Humans have heavily modified the Fraser River estuary, including installing a series of jetties throughout the leading edge of the delta to train the course of the river (Atkins et al., 2016; Church and Hales, 2007). Though there is uncertainty in the literature regarding whether or not the leading edge brackish marshes of the Fraser River have been expanding or receding over the last 85 years (Atkins et al., 2016; Kirwan and Murray, 2008; Church and Hales, 2007; Hales, 2000), analysis of recent data collected since 2011 allows us to unequivocally conclude that approximately 160 ha of the Sturgeon Bank low marsh died off from 1989 to 2011 without anyone documenting this marsh loss (Boyd et al., 2012; Google, 2017; Marijnissen, 2017; Mason, 2016).

The most detailed vegetation map and description of the Sturgeon Bank marsh (Hutchinson, 1982) may not be sufficient to completely characterize the marsh vegetation prior to recession. I compared Hutchinson's (1982) 1978 vegetation map to unpublished data from a 1981 vegetation survey (Boyd, 1983; S. Boyd, unpublished data) and the results of my 2016 survey of *B. maritimus* corms to better understand community composition of the receded *S. pungens* low marsh vegetation zone. I conclude that *B. maritimus* composed a greater proportion of the receded marsh than previous surveys indicate.

The Sturgeon Bank Marsh Recession Project Working Group and Marijnissen (2017) have proposed many hypotheses and feedback mechanisms to explain the Sturgeon Bank marsh recession. Hutchinson (1982) describes how the elevation – salinity – substrate water content interaction largely determines the plant distribution of *S. pungens* and *B. maritimus*; understanding the mechanisms of *S. pungens* and *B. maritimus* death helps us to identify possible driving factors for marsh recession. Given that the SNJ diverts fresh water away from Sturgeon Bank and may increase salinity of water at the Sturgeon Bank marsh, I hypothesize that the salinity of water at Sturgeon Bank has increased above the tolerance limit of *S. pungens* and *B. maritimus* resulting in the death of these plants and the recession of the Sturgeon Bank low marsh (i.e., the salinity hypothesis).

I established a reciprocal transplant experiment pilot project to address some of the knowledge gaps relating to *S. pungens* at Sturgeon Bank and techniques of revegetating the receded marsh. I transplanted specimens of *S. pungens* seaward of the present-day leading edges of the receded Sturgeon Bank marsh and Westham Island reference marsh to test the salinity hypothesis. I will eventually compare survival and growth of the transplants in summer 2019 after three growing seasons; however, this experiment has yet to yield results to test the salinity hypothesis and I am unable to state whether or not elevated salinity has contributed to the Sturgeon Bank marsh recession. Establishing this experiment provides insight into the feasibility, techniques, and challenges of transplanting bulrush throughout the leading edge marshes of the Fraser River delta. Observations of an unexpected macroalgae bloom of *Ulva* spp. and damage to goose exclosures at Sturgeon Bank give us insight into the dynamic nature of the marsh and factors that may prevent marsh recovery.

The SBMRP Working Group needs to use an integrated approach to investigate the Sturgeon Bank marsh recession (Marijnissen, 2017). It is difficult to evaluate which processes caused the recession because we do not fully understand the complex interaction between these processes. We can address this knowledge gap by continuing to collect data about the recession and conducting experiments and restoration pilot projects to test recession hypotheses and mechanisms. The scope of the recession investigation should be widened because the three other large foreshore brackish marshes of the Fraser River delta have also receded; we do not know if the causes of each marsh recession are similar or related.

It is easier and more cost-effective to maintain and protect an existing ecosystem than it is to restore a degraded ecosystem (Rieger et al., 2014). I propose specific actions to better monitor and maintain the Fraser River delta leading edge brackish marshes so that we may more proactively respond to ecological degradation of the estuary. Restoration of degraded sites throughout the Fraser River delta should not be seen as a replacement to ongoing monitoring, maintenance, and protection of existing ecosystems, especially given the limited success of fish habitat compensation projects from 1983 to 2010 (Lievesley et al., 2017). The predicted effects of climate change and sea-level rise may cause us to rethink options for restoring the Sturgeon Bank marsh. It may be necessary to elevate the marshes by depositing large amounts of dredge spoil along the Fraser River delta front in tandem with shoreline protection efforts to ensure the continued existence of the ecologically important foreshore brackish marshes.

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Appendix A.

Scientific and Common Names of Plants at Sturgeon Bank

Type	Scientific Name	Common Synonyms & Alternate Names	Common Name(s)	Notes
Marsh – 75% of biomass in 1978 (Hutchinson, 1982)	*Schoenoplectus pungens*	*Scirpus americanus, Scirpus pungens*	common three-square bulrush, chair-maker's rush, beach grass, sweet grass, basket grass	Low marsh species, historically formed leading-edge monoculture. Nomenclature confusion with *Schoenoplectus americanus*
	Bolboschoenus maritimus	*Scirpus maritimus, Scirpus robustus*	seacoast bulrush, saltmarsh bulrush, alkali bulrush, bayonet-grass	Low to middle marsh species, presently composes majority of leading-edge
	Carex lyngbyei	*Carex cryptocarpa, Carex cryptochlaena*	Lyngbye's sedge	Typically middle to high marsh species
Marsh – 20% of biomass in 1978 (Hutchinson, 1982)	*Schoenoplectus tabernaemontani*	*Scirpus validus*	softstem bulrush, great bulrush	Typically middle to high marsh species
	Triglochin maritima	*Triglochin maritimum*	sea arrowgrass, seaside arrowgrass, common arrowgrass	Typically middle to high marsh species
	Typha latifolia		broadleaf cattail, common cattail	High marsh species
	Agrostis exarata		spike bentgrass	High marsh species
	Argentina pacifica	*Potentilla pacifica*	Pacific silverweed	High marsh species
	Distichlis spicata		seashore saltgrass	High marsh species
Marsh – 5% of biomass in 1978 *(Hutchinson, 1982)*	*Puccinellia pumila*		dwarf akaligrass, smooth alkali grass	
	Lysimachia maritima	*Glaux maritima*	sea milkwort, sea milkweed	
	Lathyrus palustris		marsh pea	
	Sonchus arvensis		field snowthistle, field milk thistle	
	Ranunculus cymbalaria		alkali buttercup, seaside buttercup	
	Atriplex patula		spear saltbush, common orache	
	Spergularia canadensis		Canadian sandspurry	
	Sagittaria latifolia		wapato, broadleaf arrowhead	
	Deschampsia cespitosa	*Deschampsia caespitosa*	tufted hairgrass, tussock grass	
	Eleocharis acicularis		needle spikerush, least spikerush	
Eelgrass	*Zostera marina*		common eelgrass, seawrack	Native eelgrass present offshore (L. Chalifour 2016, personal communication)
	Zostera japonica	*Zostera nana, Zostera americana, Zostera noltii, Nanozostera americana, Nanozostera japonica*	Japanese eelgrass, dwarf eelgrass	Non-native present in areas of receded marsh, first observed at Sturgeon Bank in 1974 (Harrison and Bigley, 1982; Medley and Lauternauer, 1976)
Invasive species	*Spartina anglica*		English cordgrass, common cordgrass	Single clone found and removed August 2016 (E. Balke 2016, personal observation)
Not present	*Schoenoplectus americanus*	*Scirpus americanus, Scirpus olneyi*	Olney's three-square bulrush, chairmaker's bulrush	Nomenclature confusion with *Schoenoplectus pungens*

Appendix B.

Recommendations for Field Work at the Foreshore Marshes

WORKING ON THE BANKS

- Leading edge of the Sturgeon Bank is composed of fine sediments which are physically exhausting to walk through.
- Sea Island mud flat immediately south of the Iona South Jetty is composed of 0.6 m-deep mud and is dangerous to walk through.
- Repeatedly walking from the dike through the marsh on the same trail may kill low and middle marsh plants.
- All field workers should be able to identify *Spartina anglica*. Inform Ducks Unlimited of any *Spartina* at the Westham Island, Sturgeon Bank, or Sea Island foreshore.
- It is physically and logistically challenging to carry heavy loads long distances across marsh and mud/sand flats. Transport large quantities of materials via boat or in collaboration with the Canadian Coast Guard hovercraft. Consider contacting private hover craft owners to carry materials long distances across the flats.
- Field work at night during winter low tides is challenging but feasible. Take extra caution walking through ice and snow throughout the high and middle marshes.
- The remnant islands at Sturgeon Bank are accessible at a 2.5 m ebb tide until a 2.25 m flow tide (chart datum).
- The leading edge of the Westham Island marsh are accessible at a 2.0 m ebb tide until a 2.0 m flow tide.

GOOSE EXCLOSURES

- 60 kg polyethylene test for Sturgeon fishing was not strong enough to survive conditions at Sturgeon Bank.
- PVC posts are recommended over wooden posts because wood decomposes very fast in brackish water.
- Snow fencing to exclude geese likely will also trap a lot of algae and debris.
- Holographic scare tape loses its reflective quality and becomes useless in brackish and saline waters.
- Do not attach stainless steel aircraft cables to PVC with aluminum sleeves. Use stainless steel sleeves or tie the cable into knots. The aluminum sleeves will corrode due to galvanic corrosion in brackish or saline water.
- Goose exclosures on mud/sand flats or marsh will require a permit from Transport Canada under the Navigable Waters Protection Program. Transport Canada will likely require any goose exclosures, structures, or scientific instruments are identified by solar marine lanterns.

OPERATING A BOAT ON THE FLATS

- Inform the Canadian Coast Guard each time you beach your boat on the flats.
- When driving to the Lulu Island foreshore, drive boat through the Garry Point Slough instead of driving around Sand Heads.
- When driving through the Garry Point Slough, navigate by GPS with waypoints derived from lidar.
- Frequently operating a boat with outboard motor on shallow flats may damage the propeller. Be sure to carry an extra propeller along with the tools to replace it.
- The easiest place to access the Westham Island marsh with a boat is the south end of the marsh along Canoe Pass. The tide window is also shorter at this location.
- It is easier to transport large loads to the marshes via boat than to carry multiple loads between the dike and the marsh.

HEALTH AND SAFETY

- Prepare a health and safety plan for all field work. Revise the plan when appropriate.
- Never work at one of the marshes or flats alone.
- Establish and always adhere to check-in and emergency procedures.
- *Ulva spp*. can accumulate in large quantities along the leading edge of the Sturgeon Bank and Sea Island marshes. In July and August these accumulations will decompose and release hydrogen sulfide which can make humans nauseous. Do not spend extended amounts of time in these areas when they smell like rotten eggs.

Appendix C.

Costs of the Reciprocal Transplant Experiment

Category	Item	Description	Units	Unit Rate	Quantity	Cost
Reciprocal Transplant Experiment Costs: May 2016 - March 2017						
Labour	Biologist	Four months full-time employment to establish experiment (May to Aug. 2016)	hour	$20.80	637.5	$13,260.00
	Field Technician	Four months full-time employment to establish experiment (May to Aug. 2016)	hour	$18.72	637.5	$11,934.00
	Biologist	Part-time employment for monitoring (Sep. 2016 to Mar. 2017)	hour	$20.80	64	$1,331.20
	Field Technician	Part-time employment for monitoring (Sep. 2016 to Mar. 2017)	hour	$18.72	17	$318.24
	Volunteers	Help with field work (in-kind expense)	hour	$15.00	55.25	$828.75
					Labour Total:	**$27,672.19**
Certifications	Boating Safety Course	Pleasure Craft Operator Card (PCOC)	course	$41.95	1	$41.95
	First Aid Course	Occupation First Aid Level 1	course	$95.00	1	$95.00
	Boating Safety Course	Marine Emergency Duties (MED A3)	course	$211.25	2	$422.50
	Boating Safety Course	Small Vessel Operator Proficiency (SVOP)	course	$592.25	2	$1,184.50
					Certifications Total:	**$1,743.95**
Materials	Wooden stakes	For marking locations of cores	stake	$1.21	355	$429.55
	Cable ties	For miscellaneous	-	-	-	$6.59
	Nursery stock plugs	*Schoenoplectus pungens* from Peel's Nursery	plugs	$1.00	120	$120.00
					Materials Total:	**$556.14**
Goose Exclosures Materials	PVC	3''x10' perforated PVC drainfield pipe	10' pipe	$10.47	133	$1,392.51
	Polyethylene line	135 lb test braided polyethylene sturgeon fishing line	yards	$0.16	4224	$683.02
	Holographic scare tape	Goose deterrant attached to goose exclosures	roll	$9.66	4	$38.64
	Navigation lights	SeaLite SL15 solar marine lantern	light	$309.75	13	$4,026.75
	Navigation light	Carmanah solar marine lantern	light	$333.31	1	$333.31
	Gorilla tape	For limiting the range of the solar marine lanterns	roll	$11.03	1	$11.03
	Stainless steel line	500 ft 1/16'' stainless steel aircraft cable	roll	$74.45	13	$967.80
	Oval sleeves	1/16'' aluminum oval sleeve to attach aircraft cable	sleeve	$0.07	400	$26.88
					Goose Exclosures Materials:	**$7,479.94**
Equipment	Chest waders	Chest waders (2) and wading boots (2)	-	-	-	$744.72
	Aquaseal	For repairing chest waders	tube	$10.93	2	$21.86
	Field camera	Canon Coolpix Waterproof camera (1) and Lexar SD card (1)	-	-	-	$155.00
	Headlamp	Headlamp for field work at night	-	$53.76	1	$53.76
	Booties	Surf booties	pair	$43.68	2	$87.36
	Batteries	AA and AAA for GPS unit and SPOT unit	-	-	-	$46.43
	Tools	End nipper, hand measuring tape, key chain float, exacto knife bladers	-	-	-	$31.64
	Office supplies	Mechanical pencil, notebook, krazy glue, dry erase markers, sharpies, white board	-	-	-	$29.56
	Field notepaper	Field binder, waterproof field sheets	-	-	-	$50.15
	Hard plastic tote	102 L hard plastic tote	tote	$14.53	3	$43.59
	Corer/sled	Bulrush corer and custom-built sled	-	-	-	$200.00
					Equipment Total:	**$1,464.07**
Boat Costs	Moorage	Ladner Harbour, 15 ft minimum moorage	month	$141.66	3	$424.98
	Boat fuel	190.27 L regular unleaded gasoline	-	-	-	$231.33
	Gas can	Gas can 10 L	can	$18.46	1	$18.46
	Emergency Radio	VHF75 Floating HH Radio	-	$154.55	1	$154.55
	Safety gear	Throwbag 50 ft	-	$33.59	1	$33.59
	GPS emergency messenger	SPOT GPS messenger unit (in-kind expense)	-	$190.39	1	$190.39
	Supplies	Bungee cords, rope, copy of key	-	-	-	$41.03
					Boat Costs Total:	**$1,094.33**
Transportation	Car Mileage	For summer field work	km	$0.14	4286	$600.04
	Car Mileage	For fall/winter monitoring	km	$0.14	569	$79.66
	Car Mileage	For fall/winter monitoring	km	$0.18	487	$87.66
	Car Mileage	Using BCIT vehicles (in-kind expense)	-	-	-	$250.00
	Parking/tolls	Pay parking and bridge tolls	-	-	-	$24.55
					Transportation Total:	**$1,041.91**
					Labour Total:	**$27,672.19**
					Certifications Total:	**$1,743.95**
					Materials Total:	**$556.14**
					Goose Exclosures Materials Total:	**$7,479.94**
					Equipment Total:	**$1,464.07**
					Boat Costs Total:	**$1,094.33**
					Transportation Total:	**$1,041.91**
					TOTAL:	**$41,052.53**