Sturgeon Bank Marsh Recession: A Preliminary Investigation into the use of Large Woody Debris as a Tool for Restoring a Degraded Foreshore Marsh

by

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Abstract

Large woody debris removal has been ongoing in the Fraser River Delta since the late 1800's. I investigated how offshore winds and the absence of large wood may have contributed to the recession of the Sturgeon Bank Marsh. I suggest large wood increases marshland resilience and promotes new marsh establishment by attenuating wave energy, decreasing sediment mobilization, deterring herbivory, and promoting the establishment of vegetated islands from which the marsh can expand. I analyzed historical wind data for patterns in offshore wind duration and installed several pieces of large wood onto the tidal flats of the Sturgeon Bank. I developed a technique for anchoring wood in the intertidal and give my recommendations for further development. Finally, I conclude the recession of the Sturgeon Bank Marsh was the result of multiple interacting stressors and coin the term keystone structural element to describe the function of large wood within a foreshore marsh.

Keywords: large woody debris; keystone structural element; marsh recession; ecological restoration; wave sheltering; coastal marsh

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Chapter 1.

Introduction

1.1. Estuaries

Estuaries are the tidally-influenced portion of the mouth of a river where fresh and saltwater mix. The blending of attributes from three different environments, terrestrial, freshwater, and marine, make estuaries inhospitable ecosystems. This results in low species diversity and high specialization. Those species that can tolerate the extreme conditions generally face little competition due to the constant changes in salinity, inundation, and wave action. Higher elevations within the intertidal can form thickly vegetated marshes colonized by dense stands of sedges or grasses. Such marshes are subject to frequent periods of inundation. The duration, length, and frequency of inundation has a strong influence on what species can survive. As a result, species diversity generally declines with decreasing elevation. The furthest edges of emergent vegetation in a coastal marsh (i.e. the most exposed, flooded, and saline) generally exist as communities of just one or two species. At lower elevations, where flooding, salinity, and wave action are too severe for emergent vegetation, extensive tidal flats of sand and mud form. The rich sediments here support many benthic invertebrates, algae, and seagrasses.

Estuaries in North America have been under enormous development pressure since the onset of European colonization. Rich, fertile soils make estuarine floodplains prime agricultural land and many estuarine wetlands have been surrounded by dykes and filled with drainage structures. The sheltered waters of an estuary are perfect for harbours and shipyards and act as a gateway for shipping traffic moving between the open ocean and further inland. The brackish waters of an estuary also slow the decomposition of wood. Compared to the marine environment, where wood-boring invertebrates can invade in just a few weeks, estuaries are a prime location for log storage during coastal timber harvesting (FREMP 1991). For these reasons, the world’s largest cities are often built on estuaries. In fact, 22 of the 32 largest cities in the world are built on estuaries (Ross 1995).

There are 434 estuaries in British Columbia (BC), totalling around 75,000 hectares and covering 2.3% of the BC coast. The Fraser River Estuary alone covers 21,703 hectares and is the largest estuary on the Pacific coast of North America (Flynn et al., 2006). Around 2.6 million people live in the Metro Vancouver area, approximately 55% of the provinces total population in 2017 (BC Stats, 2017).

1.2. The Fraser River Delta

The Fraser River stretches 1,370 km from the Rocky Mountains to the Pacific Ocean and is the largest and longest running river in BC, Canada. The watershed of the Fraser River is about 234,000 km^2 and covers nearly one-quarter of BC's total land area (Clague et al., 1983; Figure 1.1).

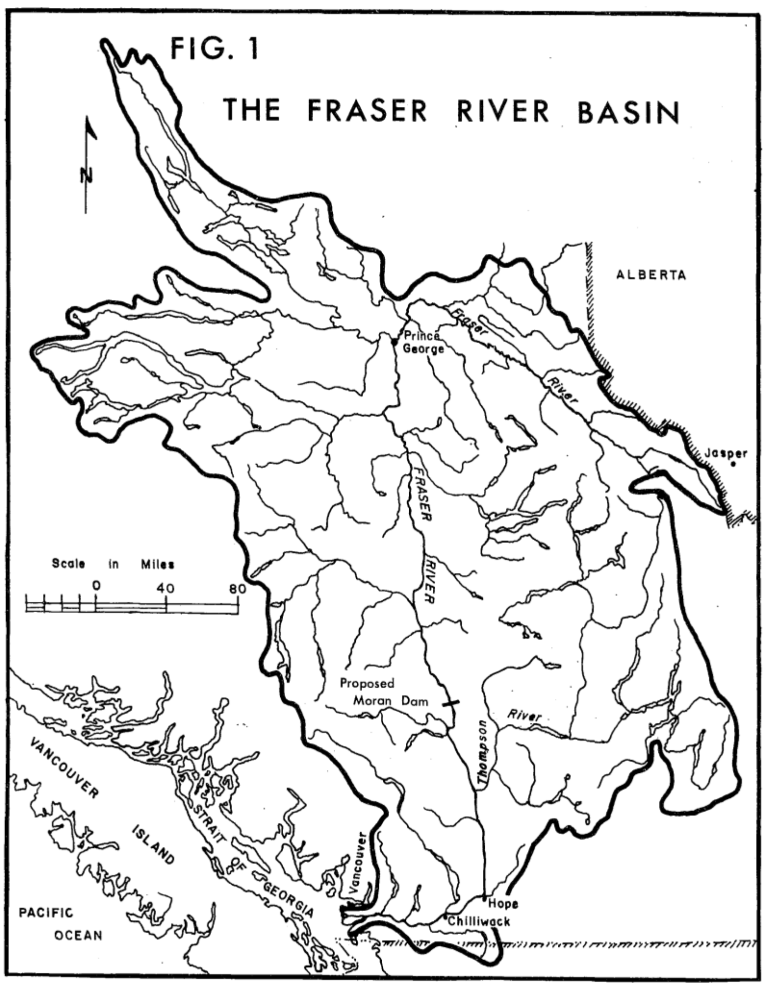

Figure 1.1. Overview of the Fraser River Watershed, British Columbia, Canada (Age and Woolard, 1976).

Following the retreat of the late Pleistocene Cordilleran Ice Sheet around 10,000 years ago, sand-rich sediments deposited at the mouth of the Fraser formed the Fraser River Delta (Clague et al., 1983). Within the delta, the Fraser River splits into four distributary channels: The North Arm, Middle Arm, Main Arm, and Canoe Pass. Approximately 85% of the total volume of the Fraser River flows through the Main Arm (Williams et al., 2009). The delta covers an area of about 1,000 km^2 and is the location of BC's largest and most populous city, Vancouver. The Metro Vancouver area includes the city of Richmond, immediately to the south, which is bordered on the west by the Strait of Georgia and the Sturgeon Bank. Richmond is built upon Lulu Island (Figure 1.2). The Sturgeon Bank, along with Roberts Bank and Boundary Bay, is part of a 23-km wide delta front composed of extensive intertidal flats and foreshore marshes (Hutchinson, 1988).

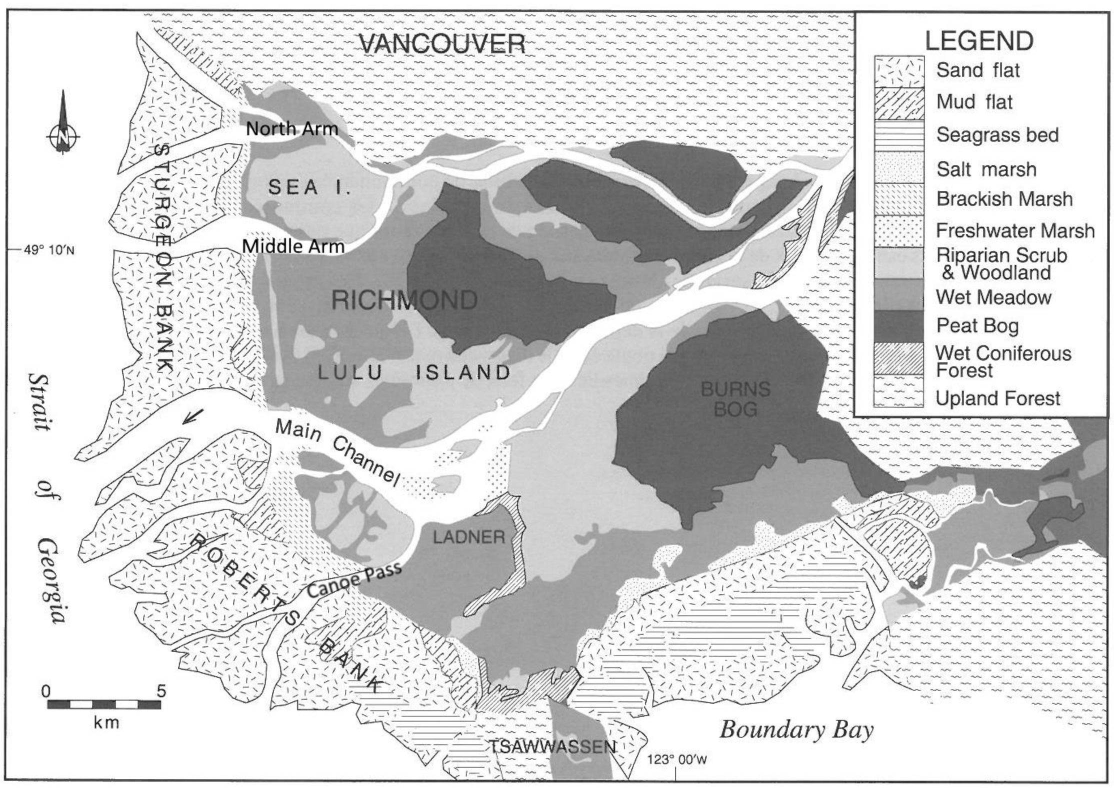

Figure 1.2. Location of the Sturgeon Bank, British Columbia, Canada (modified from Hutchinson et al. 1998).

1.3. First Nations

The Sturgeon Bank is part of the traditional territory of the Coast Salish peoples and has been occupied by the Musqueam and Tsawwassen nations for thousands of years. The earliest archeological sites on the southwest coast of British Columbia date back over 9,000 years.

The xʷməθkʷəy̓əm (Musqueam), or “People of the River Grass”, are named for the məθkʷəy̓ grass which grows along the banks of the Fraser. The story is as follows:

> "It was noted that in some periods the məθkʷəy̓ grass flourished, and in some periods it could scarcely be found. It was also noted that in some periods our people would flourish and in some periods the population would dwindle, perhaps by plague or war. It was in this way that we became known as Musqueam" (Musqueam, 2017).

The Musqueam traditional territories cover what is now Vancouver and the surrounding areas. The Musqueam Indian Reserve is located on the north side of the mouth of the Fraser River North Arm, surrounded by Metro Vancouver.

The Tsawwassen traditional territories range from Pitt Lake, to the mouth of the Fraser River, across the Strait of Georgia to the islands of Salt Spring, Pender, and Saturna, and continues north to Point Roberts and the Serpentine and Nicomekl river watersheds. The Tsawwassen would travel throughout the Strait of Georgia fishing and harvesting shellfish. As with all Coast Salish peoples, salmon were central to both the diet and culture of the Tsawwassen. The Tsawwassen Reserve land is located on a traditional village site, near the present-day Point Roberts shipping and ferry terminals (Tsawwassen, 2017).

1.4. Research Objectives

Between 1989 and 2011 the Sturgeon Bank Marsh was observed to recede shoreward by up to 500 m for a total loss of area of around 160 ha. The objectives of my research are two-fold: to contribute to the Sturgeon Bank Marsh Recession Project (SBMRP), whose primary objective is to understand the causes of the recession, and to investigate the history, loss, and potential for restoration of Large Woody Debris (LWD) within coastal marshes in the Fraser River Delta.

Chapter 2.

Sturgeon Bank Marsh Recession

On the western shore of Lulu Island lies the Sturgeon Bank Marsh. Although the Sturgeon Bank technically includes the Sea Island foreshore and Iona Beach, correspondence within the provincial and federal governments refers to the Sturgeon Bank Marsh specifically as the Lulu Island foreshore marsh. In keeping with this precedent, the Sea Island and Iona Beach marshes are treated as separate and are not included when referring to the Sturgeon Bank Marsh in this paper.

2.1. Recession Overview

There are no exact records of conditions within the Sturgeon Bank Marsh prior to European colonization. The earliest and most comprehensive documentation of the vegetation within the Sturgeon Bank Marsh comes from Hutchinson (1982), who mapped the extent and composition of the marsh and divided it into three elevational subzones: low, middle, and high. The low marsh contained predominantly two species of plants: *Scirpus americanus* (now *Schoenoplectus pungens*) and *S. maritimus* (now *Bolboschoenus maritimus*). A mix of *B. maritimus, Carex lyngbyei,* and *Trigochlin maritimum* composed the middle marsh. *Typha latifolia, Potentilla pacifica, Agrostis exarata, Distichlis spicata,* and *C. lyngbyei* composed the high marsh (Figure 2.1).

Beginning in 1989, Dr. Sean Boyd (Environment and Climate Change Canada) began taking measurements of *S. pungens* stem density within the Sturgeon Bank Marsh. Boyd returned to site in 2011 and observed that areas previously covered in vegetation had converted to open sand and mud flats. In response to these observations, the Ministry of Forests, Lands, Natural Resource Operations, and Rural Development and Environment and Climate Change Canada assembled a team of government and non-government scientists known as the Sturgeon Bank Marsh Recession Project (SBMRP) to investigate the causes of this recession. To date there has been no complete explanation on why the recession occurred. The primary objective of the SBMRP is to investigate the mechanisms which may have caused this recession.

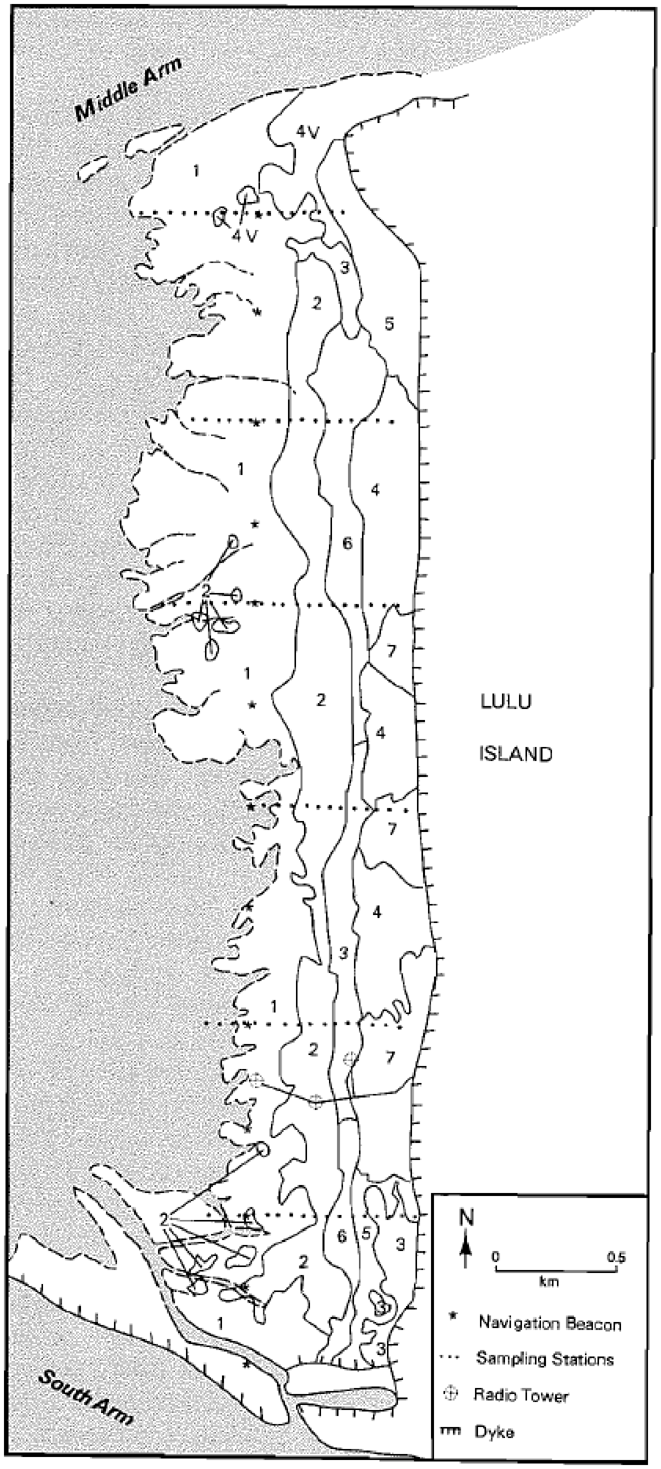

Figure 2.1. **Vegetation map of the Lulu Island foreshore marsh. Map based on field survey and interpretation of 1:12000 imagery. Dominants are as follow: 1, *Schoenoplectus punens*; 2, *Bolbochoenus maritimus*; 3, *Carex lyngbyei*; 4, *Potentilla pacifica – Distichlis spicata* (V, with significant admixture of *Scirpus validus*); 5, *Typha latifolia*; 6, *Troglochin maritimum*; 7, *Agrostis exarata* (Modified from Hutchinson, 1982).**

An assessment of the extent of the recession showed the leading edge of the marsh had receded shoreward by up to 500 m and an area of approximately 160 ha of vegetation, predominantly *S. pungens* and *B. maritimus*, had converted to open sand and mud flats between 1989 and 2011 (Figure 2.2). The Sturgeon Bank Marsh experienced the greatest loss of area in this period, though varying degrees of recession and expansion have been observed elsewhere in the Fraser Delta (Hales, 2000). There are several proposed hypotheses to explain the recession. It may be possible that a single mechanism can explain the entire recession, but the recession may also be the result of multiple interacting factors. This remains a topic of active debate. To date there have been two other M.Sc reports completed in collaboration with the SBMRP (Balke, 2017; Marijnissen, 2017).

2.2. History of Disturbance

Extensive human modifications in the Fraser Delta began in the early 1800's and included dredging, river diversion, entrainment structures, dykes, and the extensive conversion and loss of wetlands for agriculture and other uses (Table 2.1; Atkins et al., 2016). Dredging and removal of LWD in the Fraser Estuary began sometime in the 19th century. Dredging removes sediment from the channel of the river that naturally would have migrated towards the delta front but also deepens the channel of the river, slowing current velocities and causing deposition to occur earlier in the channel. Construction on the Richmond Dyke System began in 1906. In tandem with pump stations and drainage structures, the Richmond Dyke System restricts groundwater and overland flow within Lulu Island as part of Richmond's flood control program. Construction of the Steveston North Jetty began in 1912. The jetty extends over 8 km offshore and trains the flow of the Fraser River Main Arm out into the Strait of Georgia, restricting the flow of freshwater and sediments onto the Sturgeon Bank. The Fraser Estuary has been subject to extensive human development for almost 200 years. At present, Richmond now lies below the high-water mark of the Fraser River. Lulu Island historically would have been part of the floodplain of the Fraser River (Cook, 2000).

Figure 2.2. **Comparison between 1986 leading edge (red) and 2016 leading edge (green) of the Sturgeon Bank Marsh. Included in the 2016 outline are a series of remnant vegetated islands of *S. pungens*. 1986 leading edge from aerial photo interpretations (E. Balke, pers. comms.). 2016 leading edge from GPS survey using Trimble Geo 7X handheld unit (B. Mason, unpublished data).**

Table 2.1. Summary of Major Historical Influences on Sturgeon Bank (Modified from Atkins et al, 2016).

Date	Event	Implications
1800's to present	Dredging commences	Sediment removal Channel deepened
1894	Largest documented flood (>1948)	Large sediment pulse
1906 to present	Dyke construction	Flood prevention Flood sediment distribution restricted
1912	Steveston Jetty construction	Channel stabilized Marshes isolated from sediments
1913	North Arm dredging	Sediment removal Channel deepened
1917	North Arm Jetty construction	Channel stabilized Marshes isolated
1930's	South Jetty construction	Channel constricted Marshes isolated
1935	Steveston Jetty extension	Channel stabilized further westwards
1948	Flood of record	Large sediment pulse
1951	North Arm Jetty extension	Channel stabilized further westwards
1954	Nechako diversion	Fraser River watershed area reduced
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 Jetty construction	Water and fish (and sediment) released onto Sturgeon Bank
Late 1990's	Borrow dredging reduced	Sediment removals reduced
2007	Large flood event	Large sediment pulse

2.3. Potential Causes

2.3.1. Salinity

Hypothesis: The construction of the Steveston North Jetty, by directing the flow of the Fraser River Main Arm away from the Sturgeon Bank and out into the Strait of Georgia, has inhibited mixing between freshwater and saltwater within the Sturgeon Bank Marsh, potentially increasing salinity above the tolerance levels of *S. pungens* and *B. maritimus*.

There are no records of salinity levels in the Sturgeon Bank Marsh prior to construction of the jetty but the foreshore marshes on Westham Island on the southern side of the Fraser River Main Arm are thought to represent an appropriate reference site (Balke, 2017; S. Boyd, unpublished data). Surface water and interstitial salinities are higher in the Sturgeon Bank Marsh than the Westham Island marsh. Thomas and Bendell-Young (1999) took samples outside the leading edge of both marshes at 0-, 6-, and 20-cm depths and found practical salinities of 10, 13, and 15, respectively, outside the Sturgeon Bank Marsh compared to practical salinities of 2, 4, and 5, respectively, outside the Westham Island marsh. Likewise, measurements taken in July and August 2015 showed surface water salinities of 14-15 ppt at the Sturgeon Bank Marsh and salinities of 9-10 ppt outside the Westham Island marsh (S. Boyd, unpublished data). As part of the SBMRP, high-resolution water meters were installed outside the current leading edge of both marshes to record salinity, as well as temperature, pressure, and total dissolved solids at 5-minute intervals. Preliminary results from these meters show salinities can vary greatly, even within a single tide cycle, but that salinities are generally greater at the Sturgeon Bank Marsh than the Westham Island marsh (E. Balke, pers. comms., B. Gurd, unpublished data).

High salinity can create an osmotic effect which prevents the uptake of water into the plants roots, causing water deficiency in the plant. Ions present in saltwater can also exert a toxic effect or they may competitively inhibit the uptake of other required ions (summarized by Balke 2017). Through these effects, it is possible that elevated salinity levels may have caused the large-scale die-off of marsh vegetation on the Sturgeon Bank. Decomposition of the roots and rhizomes of marshland vegetation would destabilize soils, leading to collapse and erosion of the marsh platform. However, the timeline of this hypothesis does not match with the observed recession. The Steveston North Jetty and the diversion of freshwater away from the Sturgeon Bank Marsh and into the Strait of Georgia is the most likely source of any such change in salinity, but the jetty was constructed in 1912, nearly 75 years prior to the onset of the observed recession.

2.3.2. Sediment Starvation

Hypothesis: The construction of the Steveston North Jetty, along with continued dredging in the Fraser River Main Arm, has cut off the Sturgeon Bank Marsh from it’s primary source of sediments, leading to a sediment deficit within the marsh and increased susceptibility to erosion.

The Fraser River Main Arm would have been the primary source of sediment onto the Sturgeon Bank. An estimated 95% of the Fraser River’s sediments are delivered through the rivers main arm (Williams et al., 2009). The Steveston North Jetty directs the flow of the Fraser River Main Arm away from the Sturgeon Bank and extends roughly 8 km's offshore, effectively cutting off the Sturgeon Bank Marsh from its primary source of sediments. In addition, dredging has been ongoing since the early 1800's. By deepening the river, flow velocities and the capacity to transport coarser sediments are decreased. Modifications were made to the Steveston North Jetty in 1978 to allow for the exchange of water and fish between the channel and the Sturgeon Bank. Four gaps within the jetty were constructed at an elevation between low and high tide, enabling intermittent flooding with each tide cycle (Levings, 2004). This allows fine suspended sediments to pass onto the Sturgeon Bank, but the supply of sand has been largely eliminated. An average 17.3 million tonnes of sediment are transported annually by the Fraser River (Williams et al., 2009). This sediment load consists of 35% sand, 50% silt, and 15% clay (McLean et al 1999). Of the 2.8 million tonnes/year of medium and coarse sand transported by the Main Arm, around 30% is thought to reach the delta front, while the remainder is dredged from the riverbed and deposited in the Strait of Georgia (Williams et al., 2009).

Estuarine ecosystems exist in a dynamic equilibrium between processes delivering sediment to and away from the coast. Assuming processes transporting sediment away form the Sturgeon Bank have remained relatively constant, decreasing the supply of sediment to the Sturgeon Bank Marsh would result in a net loss of elevation or area. Sediment deposition in coastal marshes can contribute to marshland growth and counteract the effects of marsh subsidence and sea level rise, but without an adequate supply of riverine sediments the Sturgeon Bank Marsh may have become more susceptible to other stressors such as wind-wave erosion and sea-level rise.

2.3.3. Algal Smothering

Hypothesis: Large masses of *Ulva* spp. algae observed washing onto the Sturgeon Bank can smother vegetation and cause an increase in marsh plant mortality.

Large blooms of *Ulva* spp. algae have been observed washing onto the Sturgeon Bank in recent years (personal observations; Balke, 2017). The blooms occur in mid- to late summer and can form large mats well over 30 cm thick (Figure 2.3). Algae accumulations in the wrack zone were observed through the fall and into winter (Figure

2.4). Records of such algae blooms do not appear in records before the SBMRP, so it is unknown whether this represents a new phenomenon or if it has occurred in the past. It is also unknown where these algae blooms originate. The large mats of *Ulva* spp. can cause physical damage to marsh plants, block photosynthesis, or trap water within the marsh. Decomposition of the algae can also promote anoxia and release H_2S into the immediate environment. A thick, black sludge and strong smell of sulfur was observed to persist through the fall and winter of 2017 at the current marsh edge (Pers. Obs.; Figure 2.5).

Large accumulations of *Ulva* spp. algae were also observed in shallow water pools and drainage channels on the intertidal flats of the Sturgeon Bank. Within these pools and channels, many small fish from the family *Engraulidae* were observed trapped within the algae accumulations. Many of these fish died within the period of a single tide cycle. A total estimate of mortality or abundance of these fish is difficult, but several dozen were collected within an area of around 2 metres radius and most had already died (Figure 2.6).

Figure 2.3. *Ulva* spp. accumulation at seaward edge of the Sturgeon Bank Marsh. Photo by J. McDonald, 19 August 2017.

Figure 2.4. ***Ulva*** **spp. accumulation at seaward edge of the Sturgeon Bank Marsh. Photo by J. McDonald, 15 October 2017.**

Figure 2.5. **Drainage channel in the Sturgeon Bank Marsh filled with fine sediment and decomposing *Ulva* spp. algae. Photo by J. McDonald, 15 October 2017.**

Figure 2.6. Large mass of *Ulva* spp. algae in shallow water near remnant islands of *S. pungens* (left) and fish from the family *Engraulidae* found caught and dying within algae mass (right). Photo by J. McDonald, 8 August 2017.

2.3.4. Herbivory

Hypothesis: Increased herbivory from resident and migratory geese has caused the large-scale die-off of vegetation within the Sturgeon Bank Marsh.

Lesser Snow Geese (*Anser caerulescens*) from the Wrangell Island population use the Fraser and Skagit Deltas as a stopover point on their winter migration where they feed on the roots and rhizomes of marshland vegetation. The number of geese observed using the Fraser and Skagit Deltas has fluctuated over the past several decades but has steadily increased overall since the 1950's (Table 2.2). The Canadian Wildlife Service Waterfowl Committee (CWSWC) suggests maintaining populations of Snow Geese at 50,000 – 70,000 individuals to avoid socio-economic conflicts and degradation of the estuary. The Fraser/Skagit population of Snow Geese has been consistently above 60,000 since the early 2000's, rising to over 100,000 in 2006-2007 (Figure 2.7; CWSWC, 2013; ECC 2016). The population was estimated at around 108,000 for 2016-2017 (S. Boyd, unpublished data).

Table 2.2 **Summary of average decadal population numbers for the Fraser/Skagit Lesser Snow Goose (*Anser caerulescens*) from 1950's to 1980's. Data from Boyd (1995)**

Year	Population
1950's	29,700 ± 1,900
1960's	43,100 ± 2,400
1970's	30,100 ± 4,100
1980's	47,400 ± 2,800

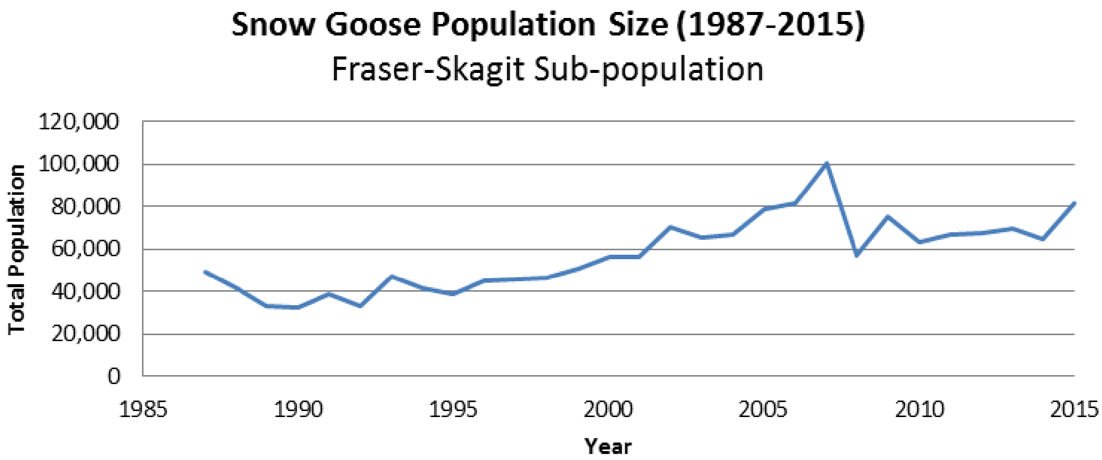

Figure 2.7. Yearly sub-population totals of the Wrangell Island Lesser Snow Geese visiting the Fraser-Skagit deltas between 1985 and 2015 (ECCC, 2016).

Resident Canada Geese, which do not migrate and are not natural to the area, have also been observed in the Fraser Delta. These geese were introduced to the BC south coast from central and eastern Canada in the 1960's and 1970's. They have since become naturalized to the area and reproduce in the wild (Smith, 2000).

Grubbing pits were observed throughout the summer of 2017 along the marsh edge and remnant islands of *S. pungens*. The pits were typically <50 cm in diameter and <5 cm deep (Figure 2.8). During this period, resident Canada geese were observed within the marsh and these pits were likely created by them. Snow Geese typically do not show up until around autumn (personal observations, S. Boyd, pers. comms.). Starting in October, large flocks of Snow Geese, numbering in the thousands, were observed on the Sturgeon Bank feeding on the senesced rhizomes of *S. pungens.* Grubbing pits observed in the fall at the north end of the marsh were roughly the same size as observed throughout the summer but covered a much larger area. All stems were removed and grubbing pits covered entire islands of vegetation except where protected by exclosure fencing (Figure 2.9). The pits were roughly 2-3 cm deep, which indicated the geese were likely only feeding on the base of *S. pungens* stems, and not reaching further down to the dormant rhizomes. *S. pungens* rhizomes in the Sturgeon Bank Marsh can reach depths over 15 cm deep (personal observations). It is possible that these geese may return to grub deeper for these rhizomes later in the season when food availability is decreased (S. Boyd, pers. comms.). The long-term effect of goose herbivory on the Sturgeon Bank is an area of active research.

Figure 2.8. Grubbing pits showing evidence of goose herbivory oberserved at remnant island of *S. pungens*. Photos by J. McDonald, 9 August 2017.

Figure 2.9. **Grubbing pits showing evidence of large-scale goose herbivory oberserved at remnant islands of *S. pungens*. Remaining patch of *S. pungens* stems surrounded by goose-exclosure fencing constructed during the summer. Photos by J. McDonald, 16 October 2017.**

2.3.5. Inundation

Hypothesis: Water depth and inundation period limit the amount of light and time available for photosynthesis, so with an increase in the depth, duration, or frequency of inundation the photosynthetic potential of vegetation within the Sturgeon Bank marsh has been decreased and resulted in increased plant mortality.

There are several mechanisms which could lead to drowning of the marsh, which I have grouped together under the hypothesis of increased inundation. Relative sea-level rise is known to threaten coastal ecosystems, especially those bound by dykes and other structures. Blocking of tidal channels by sediments or debris can inhibit drainage during ebb tide, trapping water within the marsh. Pond formation can also occur in areas of disturbance, trapping water and preventing recolonization.

Marshes respond to sea-level rise in several ways. Marshland vegetation slows water currents and traps sediments, and with sufficient sedimentation the marsh gains elevation. Also, as sea-levels rise the marsh may move further inland. This occurs as the leading edge of the marsh is drowned but new areas on the inland side of the marsh become periodically inundated and the marsh expands. By this mechanism, the marsh remains relatively intact and moves inland with the rising sea. The Sturgeon Bank Marsh is bound by the Richmond West Dyke. As sea-levels rise the dyke forms a barrier to inland migration and as a result the marsh is drowned between rising seas and an impassable barrier. Sea-level rise was assessed by Marijnissen (2017) and determined that it alone could not account for the observed recession. Accounting for crustal uplift, subsidence rates, and absolute sea-level rise, the relative sea-level rise on the Sturgeon Bank was calculated as 1.8-1.9 mm/year. With this rate of sea-level rise alone, marsh retreat would be expected at around 2-3 m/year. With roughly 500 m of recession between 1989-2011, the average rate of retreat would have been about 23 m/year.

2.3.6. Erosion

Hypothesis: Processes controlling sediment erosion and accretion on the Sturgeon Bank have changed, leading to erosion and loss of marshland area.

Tidal currents, wind-generated waves, and sediment input control the erosional-accretionary processes within the intertidal zone. It is possible that a shift in these parameters may have pushed the Sturgeon Bank Marsh into an erosional phase. Coastal marshes attenuate wave energy and provide valuable flood protection, but less understood is how wind and waves affect the growth and recession of marshes themselves. High winds and storms are a primary focus when studying coastal erosion-accretion cycles and have been linked with both marsh erosion (van de Koppel et al. 2005) and increased sedimentation (Reinhart and Bourgeois 1987). However, lower velocity winds under non-stormy conditions can also have significant impacts on the bathymetry of estuarine mudflats (Shi et al. 2017).

Hsiao et al. (2014) used Radarsat-1 images, tide level data, and a digital elevation model (DEM) to identify vertical and horizontal movement of the Sturgeon Bank Marsh and adjacent tidal flats between 2001-2008 and 2013. It was determined that over this period the leading edge of the marsh contracted shoreward by up to 150 m. A decrease in elevation was also detected along the edge of the marsh platform while a gain in elevation was detected further offshore (Figure 2.10). A shallow lagoon was observed seaward of the marsh leading edge in the summer of 2017 (pers. obs.). This lagoon contained around 5 cm of standing water throughout low tide and has been colonized by the invasive eelgrass, *Zostera japonica* (Figure 2.11).

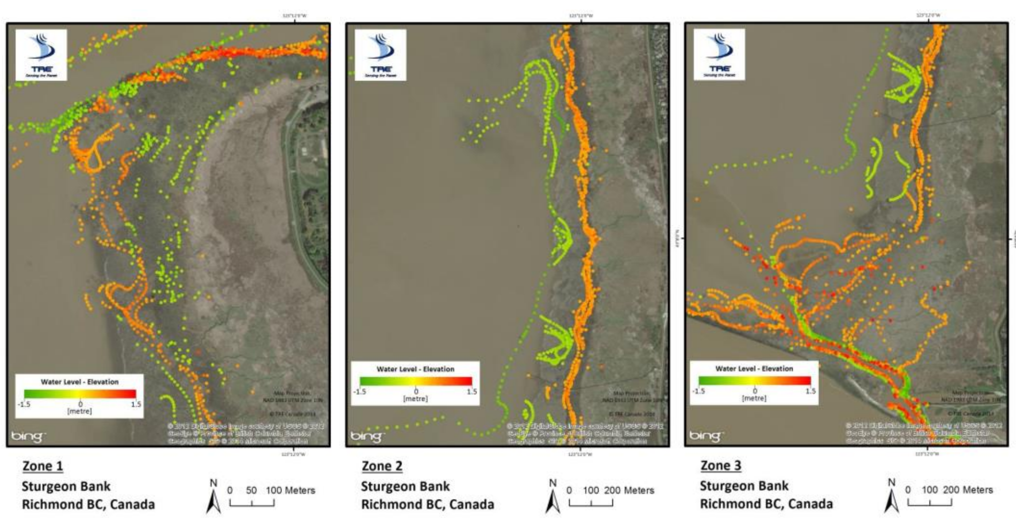

Figure 2.10 Results of the change in surface elevation analysis over the north end (zone 1), middle (zone 2), and south end (zone 3) of Sturgeon Bank. Orange dots represent a decrease in elevation >0.5 m compared to a 2013 DEM. Green dots represent a gain in elevation >0.5 m compared to a 2013 DEM (modified from Hsiao et al., 2014).

Figure 2.11 Picture showing presence of non-native eelgrass, *Z. japonica*, in shallow lagoon between 2017 marsh leading edge and remnant islands of *S. pungens*. Photos by J. McDonald, 28 June 2017 (bottom). 8 August 2017 (top).

Marijnissen (2017) analyzed historical wind data to determine if the frequency or intensity of storms had increased during the period of marsh recession. The strongest storm events occurred in 2000, 2001, and 2003, roughly 10 years after the marsh recession had already began. It was therefore determined that these storms could not explain the onset of the recession, though they may have prevented recolonization.

Offshore winds correlate with erosion and onshore winds correlate with accretion and marshland emergence (Gunnel et al. 2013; Shi et al. 2017). Wind direction is therefore an important factor to consider in marsh accretion and erosion cycles on estuarine tidal flats. As part of the research presented in this report, I investigated the hypothesis that a shift in offshore vs onshore wind patterns may have contributed to the SBMR. This information is presented in Chapter 3.

2.3.7. Loss of LWD

<u>Hypothesis:</u> The removal and interception of LWD from the foreshore of the Fraser River Delta has had an unknown effect, potentially impacting the Sturgeon Bank Marsh.

The function of LWD in estuarine marshes is not well understood. Suggested functions include contributing organic matter to the soil and detritus cycle (Yamanaka, 1975), acting as a source of terrestrial “slow-release” carbon to ocean food webs (Maser and Sedell, 1994), dampening wave energy and creating protected microclimates suitable for marsh establishment and growth (Hales, 2000), and providing many features such as perching locations for birds and shallow water pools for fish at low tide (Maser and Sedell, 1994). It has also been suggested that LWD has a negative impact on marshes by smothering vegetation and compacting or disturbing soils (Hales, 2000; Thomas, 2002). Dampening of wave energy is a core component of my research into this topic. I suggest that, along with creating sheltered microclimates for marshland establishment and growth, the presence of LWD in an established foreshore marsh increases the resilience of that marsh to wind-wave erosion. To understand how the loss of LWD may have affected the Sturgeon Bank Marsh, an understanding of the history of LWD in the Fraser Delta and how it has changed is required.

Few records exist of historical accumulations of LWD in the Fraser River Estuary. The earliest written records are from the journal of Captain George Vancouver as he sailed around Point Grey in 1792:

> [The] shoal continues along the coast to the distance of seven or eight miles from the shore, on which were lodged, and especially before these [river] openings, logs of wood, and stumps of tree innumerable (Roberts et al. 1998).

More recently, Johnston (1921) with the Canadian Geological Survey observed:

> Large quantities of driftwood are carried seaward by the river during the freshet. For a few days during the height of the freshet, there is an almost continuous procession past Steveston… It collects especially in the channels of the river, and along the shore face of the delta where it becomes buried by the advance of the delta. It is most abundant in the top-set beds of the delta.

Even as late as the 1970’s, the captain of the Samson V (Figure 2.12), Albert Gibson, stated in an interview:

> Sometimes you could walk over the driftwood from New Westminster to Surrey. We could not operate. We would take our holidays and tow the vessel on the dry dock for maintenance for at least two weeks” (Thonon 2006).

Whole trees drifting out to sea would become lodged either in the banks or the channel of the lower Fraser. These logs, or “snags”, posed a serious concern to residents along the Fraser. Drifting wood damaged fishing nets, docks, and bridges, and were dangerous obstacles to boat traffic. To mitigate the damage and danger presented by large wood in the lower Fraser the government began operation of a series of paddle-driven steamships, or “snag boats”, that would patrol the Fraser removing wood debris and dredging the channels. The first of the snag boats, the Samson, began operation in 1884 (Figure 2.12). The services provided by these ships continued until 1979, when the last of the snag boats, the Samson V, was decommissioned (New Westminster, 2017).

Wood debris removal from the lower Fraser River began on an industrial scale with the operation of the Fraser River Debris Trap, which is located between Hope and Agassiz, BC. The trap began operation in 1979 and removes between 25,000 and 100,000 m^3 of wood from the river during the annual spring freshet. 90-95% of this wood is of natural origin while the rest is debris from forestry or other industries (FREMP 1991;

Thonon 2006). The wood that is removed from the river, before it reaches the estuary, would have been the main source for naturally occurring wood debris within the Fraser Estuary and along the delta foreshore. Since the debris trap began operation, much of the LWD within the Fraser Delta is now escaped timber logs from transport booms and log storage.

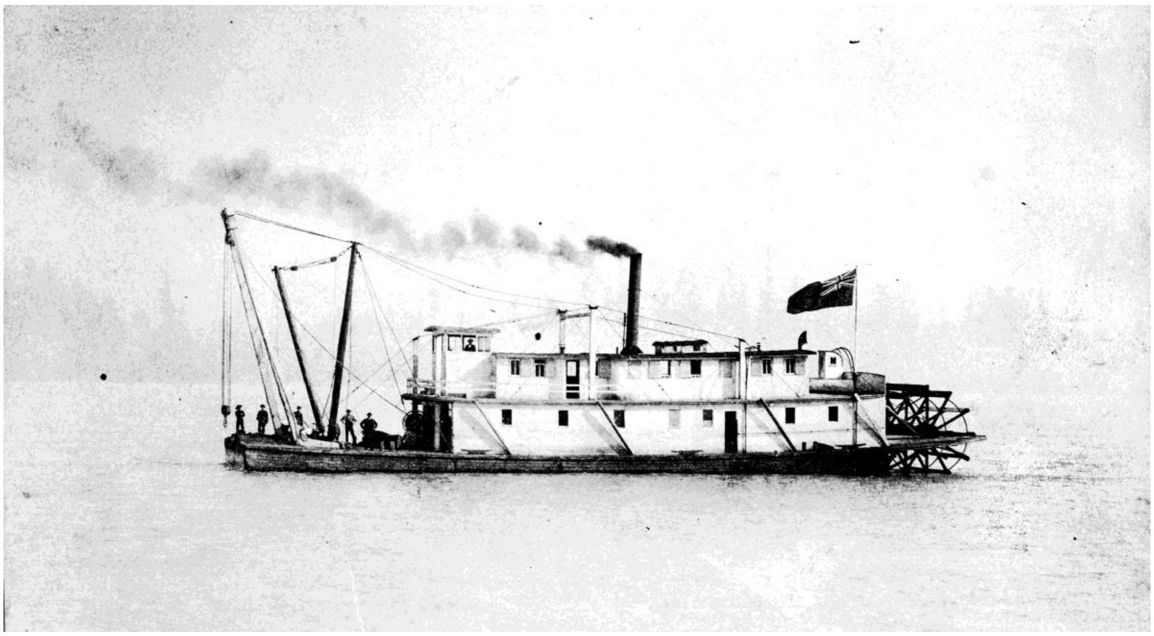

Figure 2.12. The first of the Fraser River snag boats, the Samson I in 1885 (Royal BC Museum).

Each year, millions of cubic metres of logs are transported into the Fraser Estuary for consumption and storage. During the 1980’s, an estimated 9.832 million m^3 of logs were consumed by 40 processing plants within the Fraser Estuary. In addition to what is consumed by local operations, an estimated additional 25% of logs are moved through the estuary for a total of 12.290 million m^3 (Williams et al., 2009). In 2009, there was an estimated 47 processing operations within the Lower Fraser. The 11 largest of these operations consumed around 4 million m^3, though an estimate of total consumption in the Lower Fraser was not provided in this report (Park and Pitcairn, 2014).

Industry logs bound for the Lower Fraser are first barged to Howe Sound, 40 km to the north-west, and dumped there. From here, the logs are assembled into booms and towed into the Fraser Estuary. Booms are constructed from manufactured logs called boomsticks, which are about 20 m long. Boomsticks are then joined by chains into rafts, which are 1 boomstick in width and not more than 8 boomsticks long. Where the boomsticks are joined end-to-end along the side of the raft, another log, called a “swifter”, is chained across the top of the floating logs to tie the raft together. Each 20-m x 20 m unit is called a section which are then assembled into a tow (Figure 2.13). The maximum size of a tow allowed by the North Fraser Harbour Commission for transport within the river is 32 sections, though a typical tow within the Strait of Georgia is around 72 sections (FREMP 1991). Log buoyancy depends on the species of tree, duration and frequency of water storage, and water salinity. Because boom transport relies on the natural buoyancy of wood, log sinkage is source of loss during transport. To compensate for this, logs are often bundled into groups of a dozen or more to prevent single logs from sinking. The buoyancy of the bundled logs is sufficient to prevent single logs from sinking. Estimates conclude that approximately 20% of boom transport is unbundled (flat boom) while the remaining 80% are bundle booms (Williams et al., 2009). Another source of loss during boom transport is the break-up of the boom itself. An estimate of the volume of wood lost during transport was not readily available, though the majority of shoreline wood accumulations within the Lower Fraser are currently anthropogenic (Figure 2.14).

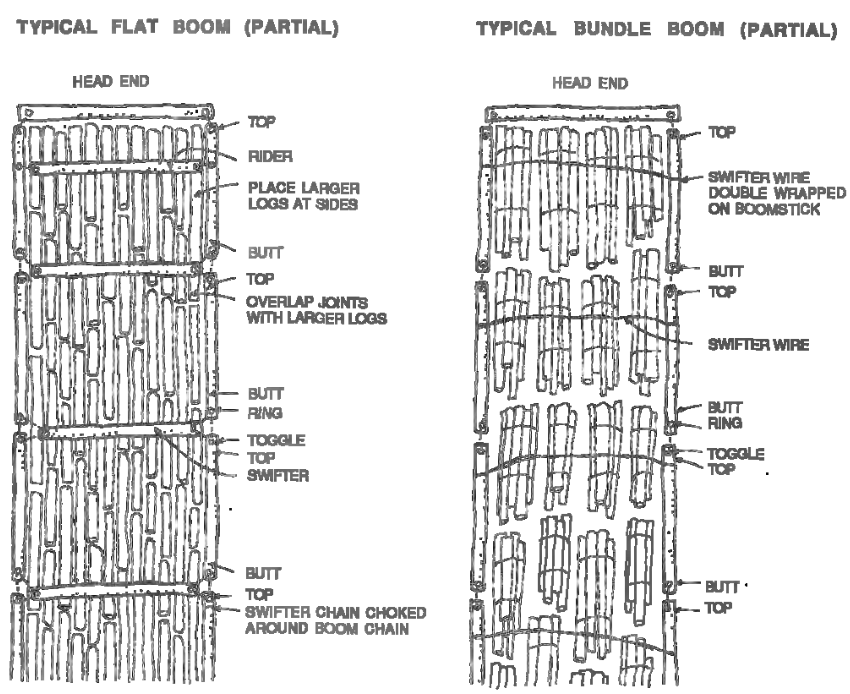

Figure 2.13. Typical log boom construction for transportation along the BC coast (FREMP, 1991).

Anthropogenic LWD behaves much differently in the intertidal than natural LWD. The primary difference being the shape and structure of the wood itself. Natural LWD have a large root wad, branches, and is often bent, bowed, or otherwise irregularly shaped. The root wad and branches dig into the substrate as it is transported inland, helping to anchor the wood in place and resist further transport. The diameter of the root wad is also much greater than the main stem of the tree itself, which causes it to dig in and anchor in place in much deeper water than it would with the root wad removed. Irregularities in the shape of the LWD can also prevent rolling, further helping prevent remobilization and to anchor the LWD in place. Anthropogenic LWD are cut at both ends with the root wad and branches removed and are generally straight, uniform logs. This allows anthropogenic LWD to be transported much further inland. With no root wad or branches to dig into the substrate, anthropogenic LWD only becomes immobile when it is pushed onshore by the strongest waves. Even then, anthropogenic LWD can be remobilized by waves once tides reach it again. The straight, uniform structure of anthropogenic LWD also enables it to pack together tighter in the wrack zone, smothering vegetation (Figure 2.15). The root wad, branches, and irregularity of natural LWD would create pockets and space between logs, enabling vegetation to persist as the LWD embeds into the substrate. Depressions in the high marsh of the Sturgeon Bank were observed and assumed to be left behind following LWD remobilization (Figure 2.16).

Figure 2.14. Escaped bundle from log boom transportation, Sturgeon Bank Marsh. Photo by J. McDonald, 29 May 2017.

Figure 2.15 **Accumulations of anthropogenic LWD within the high marsh of the Sturgeon Bank, BC, Canada. Photo by J. McDonald, 22 March 2018.**

Figure 2.16 **Depression and pool following the remobilization of anthropogenic LWD in the high marsh of the Sturgeon Bank, BC, Canada. Photo by J. McDonald, 22 March 2018.**

Chapter 3. Analysis of Historical Wind Data

3.1. Methods

Hourly wind data from the Vancouver International Airport (YVR) weather station were downloaded from the government of Canada climate database website (climate.weather.gc.ca). YVR is located on Sea Island, adjacent to the Sturgeon Bank Marsh on the opposite side of the Fraser River Middle Arm. All available data from this station was downloaded and covered the period from 1 January 1953 to 31 December 2017. The data were compiled into yearly summaries and split into onshore and offshore winds. Because the Sturgeon Bank shoreline is oriented roughly north-south, offshore winds were assessed as any measurements originating from a direction greater than 180° and less than 360/0°. All other winds were treated as originating onshore. For the purposes of this study only offshore winds were considered further. Wind speed counts of 0 km/hr were excluded. The total count of the number of hours the Sturgeon Bank experienced offshore winds for each year were compiled and plotted using R statistical software. A locally weighted scatterplot smoothing function (LOWESS) was fitted to the data to describe the overall trend for the period of 1953-2017.

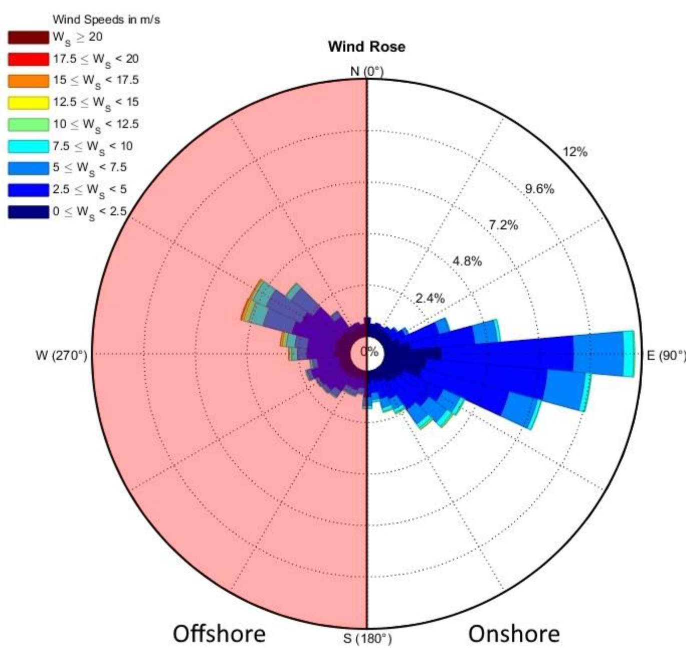

Figure 3.1 **Wind rose of YVR airport between 1992 and 2012. Shaded area shows winds considered originating offshore. Data from http://climate.weather.gc.ca (modified from Marijnissen, 2017).**

3.2. Results

A distinct period of low offshore wind duration was observed to have occurred during the early 1980's. Prior to 1980, the total duration of offshore winds per year in the area appears to have been decreasing since 1953. Offshore wind duration averaged 3329 hours/year between 1953-1959, dropping to 2869 hours/year for 1979-1984. Yearly offshore wind durations have been trending upwards since the mid-1980's to an average of 3516 hours/year for the period between 2011-2017 (Figure 3.2). This amounts to an increase of roughly 22%, or 630 hours, in offshore wind duration per year over a 30-year period beginning around 1979.

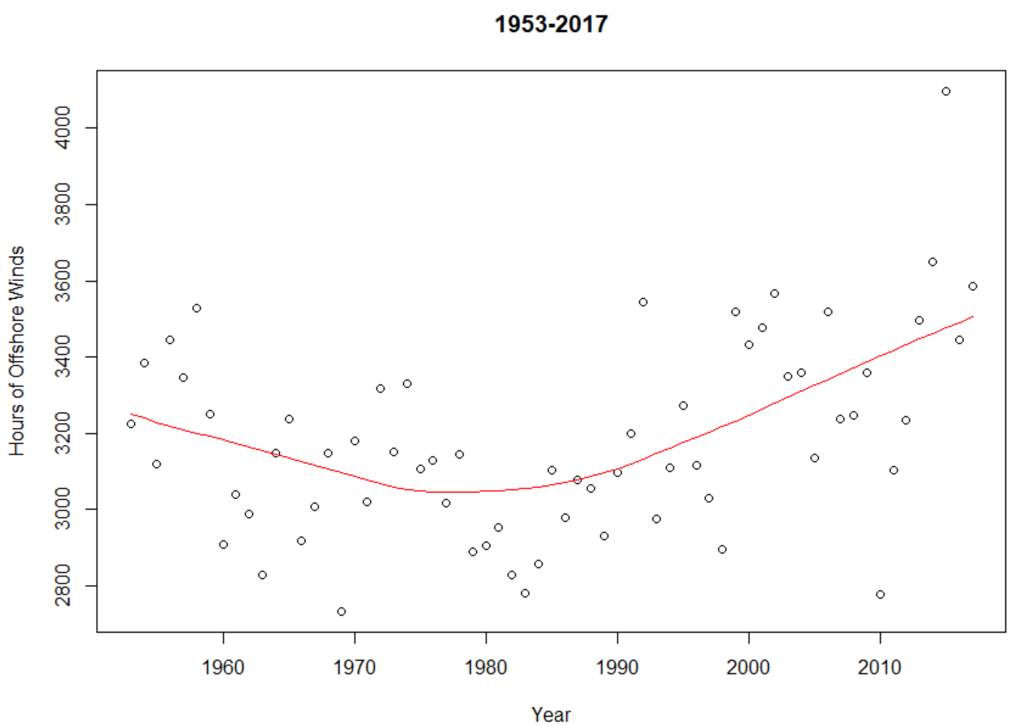

Figure 3.2. **Graph showing the number of hourly data points recording westerly winds for each year from 1953 to 2017. Data retrieved from http://climate.weather.gc.ca. Line is the result of a Locally Weighted Polynomial Regression (LOWESS) fitted to these data using R Statistical Software.**

3.3. Discussion

Interpretation of the wind data suggests two possible scenarios. First, the increase in duration of offshore winds between 1979 and 2017 is insignificant. Whether this trend of increasing offshore wind duration is sufficient to cause erosion within an established foreshore marsh is not known at this time. Second, the increase in offshore wind duration may have shifted the Sturgeon Bank into an erosional phase. If this second scenario is true, then it would be expected that conditions prior to the recession, during the period of low duration offshore winds, would be conducive to marshland stability and possibly even growth.

Foreshore marshes are highly dynamic ecosystems and can experience periods of expansion and recession. If there exists a pattern of variable offshore/onshore wind duration over a timescale of years to decades, then it is possible that foreshore marshes also exhibit a pattern of recession and expansion over a similar timescale. The Pacific Decadal Oscillation (PDO) operates on a timescale of 20-30 years. The last major shift in the PDO occurred in 1977 as the PDO transitioned from a cold-phase to a warm-phase (Mantua and Hare, 2002). The exact influence of the PDO on onshore/offshore wind patterns is unknown, but the shift in the PDO appears to correlate with the shift from decreasing offshore wind duration to increasing offshore wind duration on the Sturgeon Bank. The literature suggests that the PDO is currently in the middle of another such shift, back into a cold phase, so monitoring wind patterns to determine if a similar shift back to decreasing offshore wind duration could be very interesting. Close monitoring of the Sturgeon Bank Marsh leading edge during this period would be invaluable to this hypothesis.

Chapter 4.

LWD in a Foreshore Marsh: A New Tool for Restoration?

4.1. Introduction

Thus far, no single mechanism has been identified as capable of explaining the full extent of the Sturgeon Bank Marsh Recession. Several potential mechanisms (i.e. site stressors), as outlined in Chapter 2, have undoubtedly had an impact on the marsh, but none to the extent required to explain the full scale of the recession. I suggest that rather than a single mechanism causing the marsh recession, the recession may be the cumulative effect of multiple interacting factors causing the area of the recession to undergo a regime shift from foreshore marsh to tidal flat. Dredging of the river, construction of dykes and river entrainment structures, and the ongoing removal of LWD from the Fraser Estuary left the Sturgeon Bank Marsh in a precarious state (i.e. low ecological resilience and vulnerable to an ecological regime shift). With the resilience of the marsh impaired, the level of disturbance (e.g. herbivory, offshore winds, anthropogenic LWD, increase salinity, and green tides) to the marsh exceeded a critical threshold of marshland stability, causing the rapid and large-scale regime shift from foreshore marsh to tidal flat.

4.1.1. Ecosystem Regime Shifts

Shallow intertidal zones typically exist in one of two stable states, tidal flat or salt marsh, with an unstable transition state between them. When an ecosystem exists in one of these two end-member states (salt marsh or tidal flat), a change in the physical parameters of that ecosystem can cause the rapid transition from one state to the other (Fagherazzi et al., 2006). In other words, that ecosystem can undergo a regime shift. Ecosystems at risk of regime shift are considered precarious (Folke et al., 2004; Walker et al., 2004). Resilience is defined in two ways: engineering resilience and ecological resilience. Engineering resilience is a measure of resistance to disturbance and the speed of return to equilibrium following a disturbance. Ecological resilience is a measure of the magnitude of disturbance that can be absorbed before the system changes to another stable state (Holling, 1996). Precariousness is therefore a measure of low ecological resilience. The stressors identified for the Sturgeon Bank Marsh in Chapter 2 can be divided into those that make the system more precarious, and those that cause disturbance. Dredging of the river, construction of the Steveston North Jetty, and the loss of natural LWD would make the marsh more precarious by reducing the marshes capacity to absorb disturbance. Elevated salinity (from construction of the jetty), algal smothering, increased herbivory, and climate change (e.g. sea-level rise, changes in wind/waves) are mechanisms of disturbance.

Table 4.1 Summary and timeline of impacts to the Sturgeon Bank Marsh.

Date	Activity	Impact on Sturgeon Bank Marsh
Late 1800's	Dredging of the Fraser River begins decreasing the amount of sediment delivered to the Sturgeon Bank	Resilience decreased
1884	Removal of natural LWD from the Fraser Estuary begins	Resilience decreased
1906	Construction begins on Richmond dyke system	Resilience decreased
1912	Construction begins on Steveston North Jetty	Resilience decreased (decreased sediment input); disturbance increased (salinity increased); some new marsh created (Hales, 2000)
1977	Fraser River Debris Trap begins operation	Resilience decreased (natural LWD removed)
1979	Shift in Pacific Decadal Oscillation	Disturbance increased
Mid-1980's	Onset of Sturgeon Bank Marsh Recession	N/A
Early 2000's	Population of Lesser Snow Geese in the Fraser Delta exceeds maximum number recommended by the CWSWC	Disturbance increased
2000, 2001, 2003	Large storms impact the Sturgeon Bank	Disturbance increased
2016, 2017	Large blooms (i.e. green tides) of *Ulva* spp. algae observed on the Sturgeon Bank	Disturbance increased

I suggest there are two possible pathways for restoring the Sturgeon Bank Marsh: implementing strategies to increase the resilience of the marsh (e.g. sediment nourishment, wind-wave sheltering) or implementing strategies to mitigate disturbance (e.g. Snow Goose population control, restoring freshwater inputs). I investigated the hypothesis that natural LWD provides a unique function in a foreshore marsh as a rigid, physical structure capable of attenuating wind-wave energy in an otherwise highly dynamic and mobile environment. I suggest that natural LWD provides a keystone function in foreshore marshes, increases marshland resilience, and is therefore a potential tool for restoring the Sturgeon Bank Marsh.

4.1.2. LWD as Keystone Structural Element in a Foreshore Marsh

Keystone species are those that exert a disproportionately large influence on their environment relative to their abundance (Power et al., 1996). This makes keystone species high value targets for ecological restoration as small gains in their abundance can translate into a much larger positive effect on the ecosystem overall. The functions provided by keystone species are often also unique, giving them further priority over species that are functionally redundant (Walker, 1992; Elmqvist et al., 2003). The concept of functional uniqueness can be extended to include keystone structures as well, such as scattered trees in savannah (Manning et al., 2006). I suggest that LWD in a foreshore marsh provides a unique function by attenuating wave energy, deterring herbivory by geese, providing favourable conditions for the recruitment and retention of other species, and increasing overall ecological complexity. Complexity is often discussed along with ecological integrity, diversity, and resilience (Parrott, 2010). Keystone structures provide a unique function that is disproportionate to their size or abundance (Manning et al., 2006). However, rather than LWD in foreshore marshes providing a unique function as a standalone structure, I suggest LWD contributes to the overall structure of the marsh itself by stabilizing sediments, attenuating wave energy, and contributing to the integrity of the mat of plant roots and rhizomes that holds the marsh together. For this reason, I suggest using the term Keystone Structural Element (KSE) to emphasize the role of LWD as part of the overall fabric of a marshes surface.

Foreshore environments are constantly impacted by wind, waves, and storms. The roots and rhizomes of marsh plants bind sediments and prevent erosion of the marsh platform, while the aboveground biomass of marsh plants slows water currents, promotes deposition, and traps sediments and detritus. Aside from marsh vegetation, there are little to no rigid structures within a marsh. Accumulations of natural LWD would be the most rigid structures in the foreshore environment. New marshes often form on the leeward side of rigid structures, such as jetties or coastal developments (Hales, 2000). With sufficient input of wood and sediment, LWD could naturally provide a similar function for marshland establishment. In the Stillaguamish estuary, Washington, USA, ephemeral log rafts in the rivers channel were observed to create new areas of marshland over the course of 2-4 years (Crumb, unpublished data).

Another possible function of LWD in the foreshore environment is to interrupt the sight lines of geese. Physical barriers, such as fences, are one suggested method of goose herbivory control as geese require long lines and a running start to take flight. Geese will generally avoid closed spaces as a method of avoiding predation. It is therefore possible that LWD provides a form of natural deterrence to pressure from goose herbivory.

LWD accumulations may also act as biological legacies within an impacted marsh. Biological legacies are organisms or structures that persist in an ecosystem after a disturbance (Manning et al., 2006). If the LWD accumulation remains intact while the rest of the marsh degrades, I speculate that the physical structure of the LWD could provide a “life-boating” function which enables other species to persist within the microclimate surrounding the LWD. This concept is described in Manning et al. (2006) for scattered tree ecosystems in savannah. Such life-boating structures and remnant patches of vegetation could then become focal points from which recovery could expand, influencing the speed and pattern of natural regeneration. This is similar to the “fertility island” concept, where keystone structures provide favourable conditions for the recruitment of other species (Manning et al., 2006).

The Sturgeon Bank Marsh has undergone significant human induced changes including the removal of natural LWD from the Fraser River and its delta. As a result, much of the LWD in the marsh is now anthropogenic. Anthropogenic LWD is highly mobile in the intertidal, able to be transported much further inland, and is easily remobilized by storm surges and high tides. Conversely, natural LWD can anchor in place in deeper water and is resistant to remobilization due to its root wad and irregular shape. I suggest this makes natural LWD a stable part of the overall fabric of the marsh and increases the marshes resilience to wind and wave erosion. Furthermore, I speculate that restoring natural LWD to a degraded marsh can shift the physical conditions within that environment towards supporting marshland establishment, growth, and stability. To test my hypothesis, a field experiment was conducted that involved anchoring LWD onto the tidal flats near the historic leading edge of the Sturgeon Bank Marsh. The objective of this experiment was two-fold. To attempt to anchor LWD in place within the intertidal and to determine if LWD in a foreshore environment provides a benefit to marsh plant establishment.

4.2. Methods

Four treatment plots containing LWD and four control plots were constructed in June 2017 for a total of eight plots. The eight plots were located near the historic leading edge of the marsh and oriented in a line running parallel to the shore (Figure 4.1). Control and treatment locations within the line were randomized, with a 15-m buffer space between each plot. This location was chosen for several reasons. First, four attempts were made in other areas of the flats within the historic area of marsh. Three of these attempts failed and it was determined that the area closer to the current marsh edge was unsuitable for this technique. Second, the remnant islands of *S. pungens* are topographically higher than the area between them and the current marsh edge. The objective was to isolate the effect of the LWD on sheltering from wind and waves in an exposed intertidal environment, so these islands were intentionally avoided to prevent any additional interference or sheltering they may have provided. Third, the proximity of the remnant islands of *S. pungens* led me to believe that this location was suitable for further *S. pungens* establishment. Several of these islands were within 200 m and on either side of my installation location (Figure 4.1). Finally, transplanting was done by towing a plastic bin filled with 20 plugs at a time across the sand and mud flats, so this location also had the added benefit of making the act of transplanting logistically simpler and easier.

The four pieces of LWD used in the treatment plots measured 3.5 m in length and 30-40 cm in diameter. The LWD was secured in place using 1.9-cm (3/4”) diameter braided stainless-steel cable and galvanized steel helical ground anchors. The anchors were 1.68 m (5.5’) in length, 1.9 cm in diameter, with a single turn of a 15-cm (6”) wide auger blade at one end and an eye-loop at the other (Figure 4.2). Initially, a 1.3-HP gas-powered auger was used to sink the anchors, but this was only capable of driving them to about 1 m depth. The final depth positioned the eye-loop approximately 10 cm below the surface and was achieved by inserting a four-foot metal rod into the anchors eye-loop and turning by hand. Four anchors were used for each piece of LWD, positioned with two at each end and one on either side (Figure 4.3). The steel cable was looped through the anchors eye-loop and fastened back onto itself using stainless steel clamps. The cable was then attached to the LWD using heavy steel staples hammered into place for additional security.

Figure 4.1. Map showing the location and orientation of the 8 plots constructed for LWD experiment.

Figure 4.2. Photo showing example of a helical ground anchor used to secure LWD. Photo by J. McDonald.

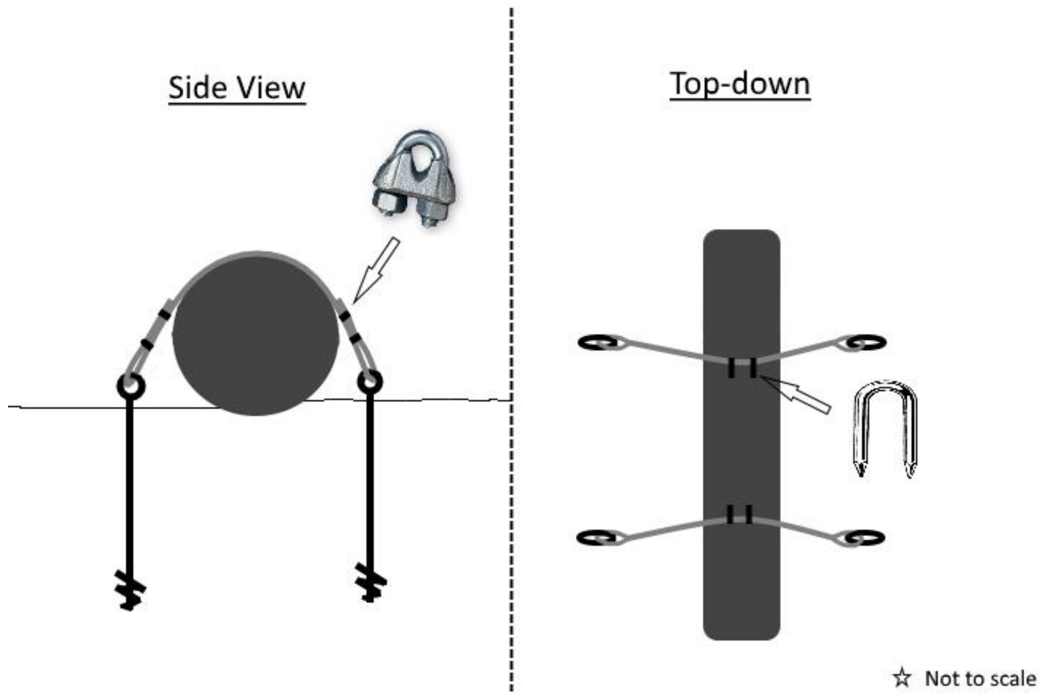

Figure 4.3. Diagram showing installation technique used to secure LWD.

To my knowledge, there are no documented attempts to anchor LWD onto a tidal flat. To test for benefits to marsh plants establishment, two species of bulrush, *S. pungens* and *B. maritimus*, were transplanted from nearby areas in the marsh and planted adjacent to the LWD. *B.* maritimus would have also been in the degraded area of marsh as identified by Hutchinson (1982) and the presence of dead *B. maritimus* corms observed in situ (personal observations). Transplants were harvested in 10-cm diameter plugs and standardized to a depth of 15 cm. Any sediment and root mass below this depth was removed with a utility knife. The plugs were then planted in clusters of 5, oriented in a cross with a 5-cm space between each plug. Each plot received 4 clusters of each species, for a total of 8 clusters, or 40 plugs within each plot. The clusters were placed at 1 m and 2 m to either side of the LWD, with the same pattern followed in each control plot and the LWD omitted (Figure 4.4).

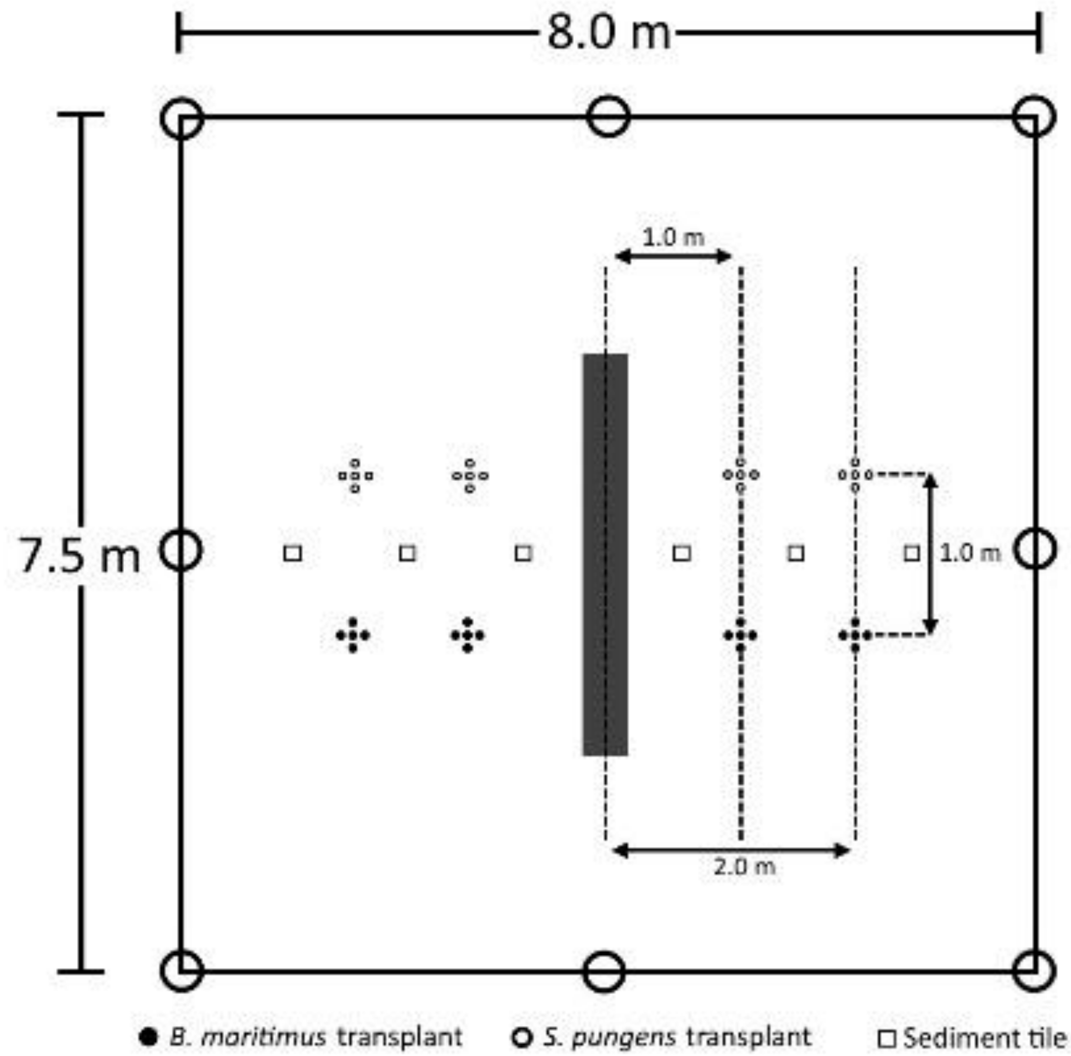

Figure 4.4. Layout diagram for LWD treatment plots. Control plots matched the exact layout of the LWD treatment plots but with no LWD.

Measurements of stem density and stem length were taken for each plug for both species of transplanted bulrush. Because *B. maritimus* is a larger plant with bulkier roots, care was taken to ensure each plug contained only a single stem (i.e. stem count of 1 for each plug). Measurements were taken in August shortly after the onset of senescence, as noticed by browning at the tips of the stem and leaves. Future measurements should be made at a similar time for an appropriate comparison. Measurements of *B. maritimus* stem length were made to the tip of the longest leaf (i.e. the longest possible measurement from base of stem to tip of leaf).

4.3. Results

Four trial attempts were made before a piece of LWD was securely positioned in the intertidal with enough confidence to continue further. Buoyancy of the LWD is the most likely cause of failure in these attempts. Wave action is a predominantly lateral force, so failure from wave impacts would likely result in stripping or breaking of hardware, whereas it appeared these failures were the result of the anchors being pulled straight upwards through the substrate. Trials 1 and 2 used only two anchors per piece of LWD. Holes were drilled through the LWD at each end and a ½-inch threaded rod inserted. A large washer and nut were fastened to the top side while the bottom side was attached to the anchor with a threaded eye-loop. Trial 1 was positioned roughly 100 m from the current leading edge of the marsh and failed on one side after the first tide cycle. Trial 2 was moved further offshore with the assumption that coarser sediment would help secure the anchors in place, though both anchors failed on this attempt after the first tide cycle. On both trials the anchor was only pulled part-way out of the soil, leaving the anchor and LWD laying atop the sediment upon the next low tide. Trial 3 was moved even further offshore into even coarser sediments. This time both anchors failed completely and the LWD and anchors were transported into the marsh roughly 300 m away. The anchors were recovered but the LWD was too difficult to retrieve and therefore left in place. Trial 4 was moved even further offshore and positioned near the existing remnant islands of *S. pungens.* The installation design was changed to the final design using four anchors and this time the installation was a success. At present time, roughly 8 months later, this LWD trial remains stable.

The first three attempts all used the same log, a piece of Yellow Cedar (*Cupressus nootkatensis*). Yellow cedar is widely used for its resistance to waterlogging and rot, which also make the wood incredibly buoyant. Following the failure of the first three trials, the fourth trial was made using a piece of Western Hemlock (*Tsuga heterophylla)* which is known to sink more readily. This is thought to contribute to the success of trial 4 and failures of trials 1-3, along with the change in installation design.

All LWD installations created a pool of water as sediments were scoured from around and beneath the LWD. During each visit it was observed that the cables securing the LWD in place would become slack, enabling the LWD to slightly move. It is likely that this small movement contributed to the scouring effect of the LWD as the log would rise, pulling in water, and fall, expelling water and sediments with each wave. Scouring from tidal currents likely also contributed to this. It is unknown the relative importance of each factor in the overall scouring effect. Several attempts to tighten the cables and prevent LWD movement were made, but the cables would become slack again with each tide cycle.

All installations held in place for roughly 6 months, from July to December 2017, although single anchors had to be repaired 3 times throughout the summer after being pulled halfway out of the sediment. In December, one installation (plot T1) failed completely on one side and was repaired after the log had rotated nearly perpendicular to its original position. In March 2018, over 8 months after the initial installation 3 installations were observed to have failed. The LWD in plot T1 has become fully dislodged and broken through the exclosure fencing. The log had been transported offsite by the tides and could not be found, though the anchors and cable remained (Figure 4.5). Plot T2 was still in place, with all four anchors, though one of the cables had snapped (Figure 4.6). Plot T3 had also remained in place, but when an attempt was made to repair the installation one anchor was found broken in half and embedded in the substrate (Figure 4.7). Plot T4 required a single anchor to be repaired and remains in place. The original trial installation (trial 4) was still intact and needed no repairs.

Figure 4.5 Broken installation hardware and no LWD in plot T1. Photo by J. McDonald, 22 March 2018.

Figure 4.6 **Broken anchoring cable at plot T2, 22 March 2018. Photo by J. McDonald, 22 March 2018.**

Figure 4.7 **Broken helical ground anchor at plot T3. Photo by J. McDonald, 22 March 2018.**

4.4. Discussion

The anchors used in this experiment were insufficient for the task. It is possible that simply bigger anchors could be successful. My recommendation would be to use a larger diameter blade on the anchor. I used 6” diameter blades and the installations required constant observation and maintenance. A longer anchor shaft to penetrate deeper into the substrate may also work. Each repair consisted of sinking the anchor back into the substrate after it appeared to be pulled straight upwards by the buoyancy of the wood. Another line of investigation could be to use wood that has been in water for a longer period. The wood used in this experiment was stored on dry land for at least 2 years prior to the experiment. It is unknown how long it takes for a log of this size to saturate in sea water. An interesting method could be to use salvaged logs already submerged or sunken, but this was beyond my abilities for this experiment.

I also recommend against using the method of cabling over the log to secure it in place. This allows too much room for movement of the LWD. With each slight shift or bounce in the logs position sediment is scoured from beneath the log giving it more room to shift and bounce. I speculate this is what caused the final failures of 3 of my installations (broken anchor, broken cable, escaped log). The method used in my first attempts could be updated to provide a more secure installation. By drilling through the log and attaching directly to the anchor using rigid hardware, the log could be fastened much tighter to the substrate. I also recommend partially burying the LWD to prevent water from flowing beneath.

Restoration should attempt to mimic the natural function and processes observed in nature. Excessive engineering of structures in degraded ecosystems does not accomplish this. From my observations within the marsh, LWD becomes anchored in place by embedding itself into the substrate. This is why root wads and irregular shapes are so important for LWD in such an environment. I used straight logs anchored to the substrate. I would recommend using large stumps, logs with root wads, or trying to mimic such a structure. Partial burial could mimic the process of the LWD becoming buried by the advance of the delta, as would occur naturally over time. Ecological restoration often seeks to speed up such processes that would naturally take years to decades (or even longer). Partial burial would therefore attempt to restore the LWD that has been removed and would have naturally become buried and embedded in the sediment profile.

I also recommend creating structures, rather than single logs. Old growth LWD would naturally anchor itself in much deeper water because of its larger diameter compared to smaller logs. Such a structure would act as a snag point for smaller wood debris, potentially creating small islands or tangles of LWD. Old-growth trees have long since been removed from shorelines, rivers, and much of the Fraser watershed. As a result, old-growth LWD is essentially non-existent in the Fraser Estuary. Regardless, a single log is likely insufficient to create any appreciable benefit to an area as large as the Sturgeon Bank. Another interesting study could be to look at the natural density of LWD in a foreshore marsh, and using this as an estimate of how much LWD is a proper target for ecological restoration.

4.4.1. Future Experiment

For a future experiment, I suggest trying to mimic the processes that would result in natural LWD accumulation over a much longer period. Whole trees being transported shoreward by waves and tidal currents would cause the root wad of these trees to embed itself into the substrate. The free end of the tree would then rotate around this point of contact until contact with another structure occurred, most likely another piece of LWD. This pattern of rotation around an anchored root wad was observed on the Sturgeon Bank over the course of summer 2017 over multiple site visits. A large piece of LWD, roughly 10-15 m in length and 0.5 m in diameter, had washed onto the Sturgeon Bank and become embedded in the substrate. This piece of LWD then rotated freely during each high tide, as observed by a series of radiating depressions surrounding the LWD, resembling a clock-face. If another piece of LWD of sufficient size had been in the immediate vicinity, I speculate that contact between these two pieces of LWD would result in an anchor point, effectively immobilizing the free end of the first piece of LWD. This is the process I would attempt to mimic. Using large piece of LWD, with root wads, and attaching the free ends of each piece of LWD to the root wad (i.e. anchor point) of another piece, creating an interlocking structure of natural LWD. Minimal hardware would be required, and only necessary as a fail-safe device at the point of attachment from one piece of LWD to another.

Various shapes or configurations could be attempted with this method. As a first attempt, I would simply create a square. This would create four points of anchoring to the substrate, provided by the root wads of four separate pieces of LWD. The four root wads would be positioned at each corner of the square, and the free end overlain atop the next piece of LWD. The free end of each piece of LWD would then be fastened to a point near the root wad of another piece, and this would be repeated for each piece of

LWD. The LWD would therefore not be fastened to the substrate, as I tried to do in my previous experiment using the helical ground anchors, but rather would be effectively free-floating above the substrate. The size of the root wad and depth of penetration into the substrate is what would keep the structure immobile. This way, log buoyancy would not be an issue so long and the size of the root wad is sufficient to prevent remobilization during the highest tides. This would require calculations based on tidal range and LWD size specific to each installation and location.

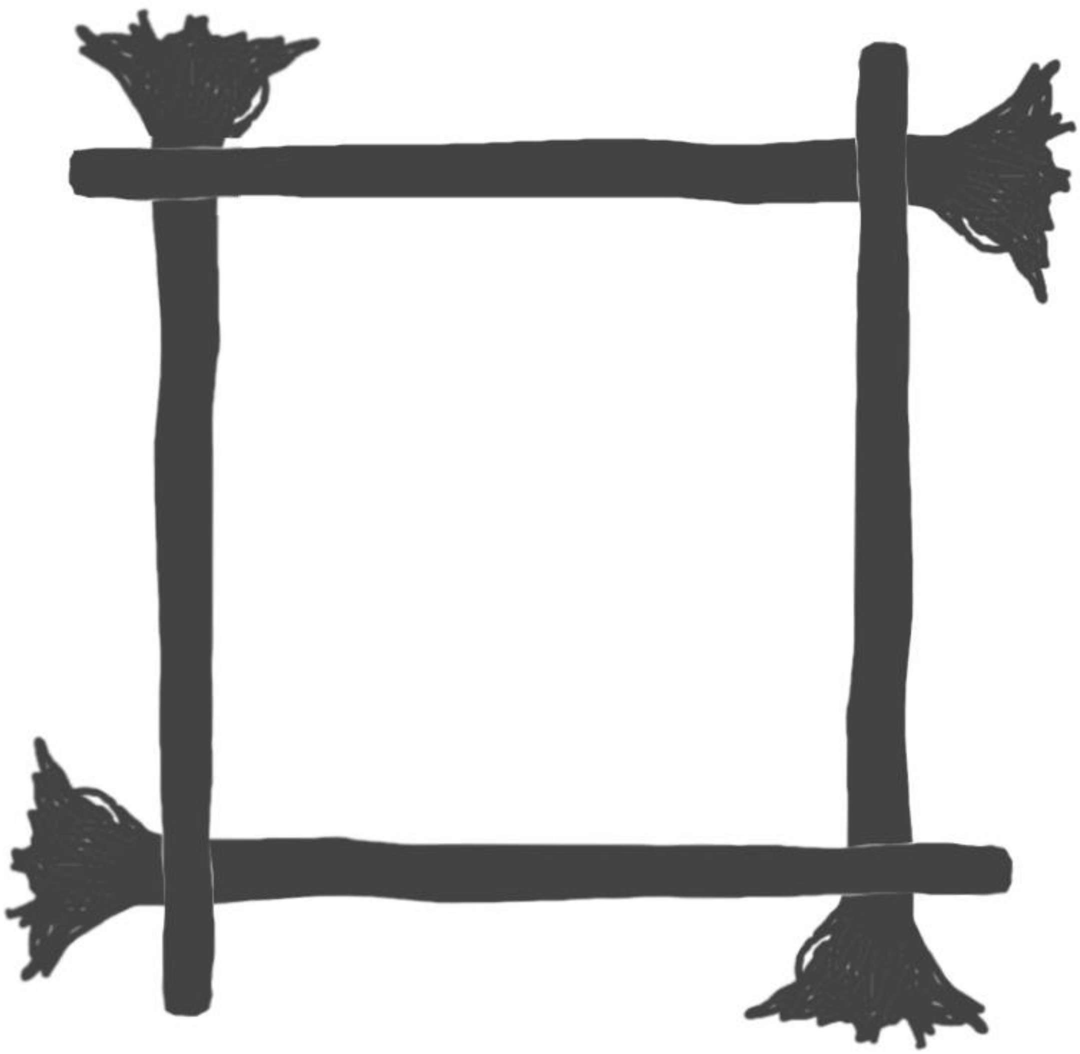

Figure 4.8 General outline of new method for anchoring LWD structures in a foreshore environment. Anchoring is provided by root wads while the free end of each piece is fastened near the root wad of another, creating a semi-rigid structure mimicking the natural process of LWD accumulation and immobilization in the intertidal zone.

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