

ENVIRONMENTAL AND HISTORICAL FACTORS  
DRIVING VEGETATION COMMUNITIES ON  
RUSSIAN ISLAND, COLUMBIA RIVER ESTUARY

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## 1.0 INTRODUCTION

### 1.1 Estuarine ecology overview

Estuaries occur at the interface between a river and a body of salt water, and they are more specifically defined as: “semi-enclosed coastal bodies of water which have a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage” (Pritchard 1967). They are dynamic systems, with accretional and erosional forces from river and tidal influences constantly re-sculpting their shape and ecosystem processes. They exhibit highly variable salinities, depending on the proportion of freshwater to tidal influence they receive (Day et al. 1989, Mitsch and Gosselink 2000). Estuaries tend to be sheltered from high-energy waves and receive ample water and nutrients from river and tide-flow, therefore setting the stage for development of productive marsh habitat (Chapman 1960, Day et al. 1989). Estuarine marshes tend to develop initially on mud or sand flats that are close to sea level, and continue to grow in elevation with sediment accretion (Day et al. 1989, Eilers 1975).

Also characteristic of these marshes are extensive networks of dendritic tidal channels that, unlike many dynamic features in an estuary, tend to remain in a fixed position once established (Day et al. 1989, Pestrong 1965, Redfield 1965). These channels fill with the tides, and as water levels rise and spill onto the surface of the marsh, suspended sediments tend to drop out along channel margins, thus producing a levee effect along the banks of tidal creeks (Day 1989, Eilers 1975). As mentioned, estuarine marshes, especially those of lower salinity, are highly productive systems, with plant communities that tend to be dominated by graminoids (tall reeds, grasses, and sedges), broad-leaved monocots, and floating plants, and energy dynamics that tend to be based on detrital food webs (Day et al. 1989, Mitsch and Gosselink 2000, Odum et al. 1974).

### 1.2 Columbia River estuary

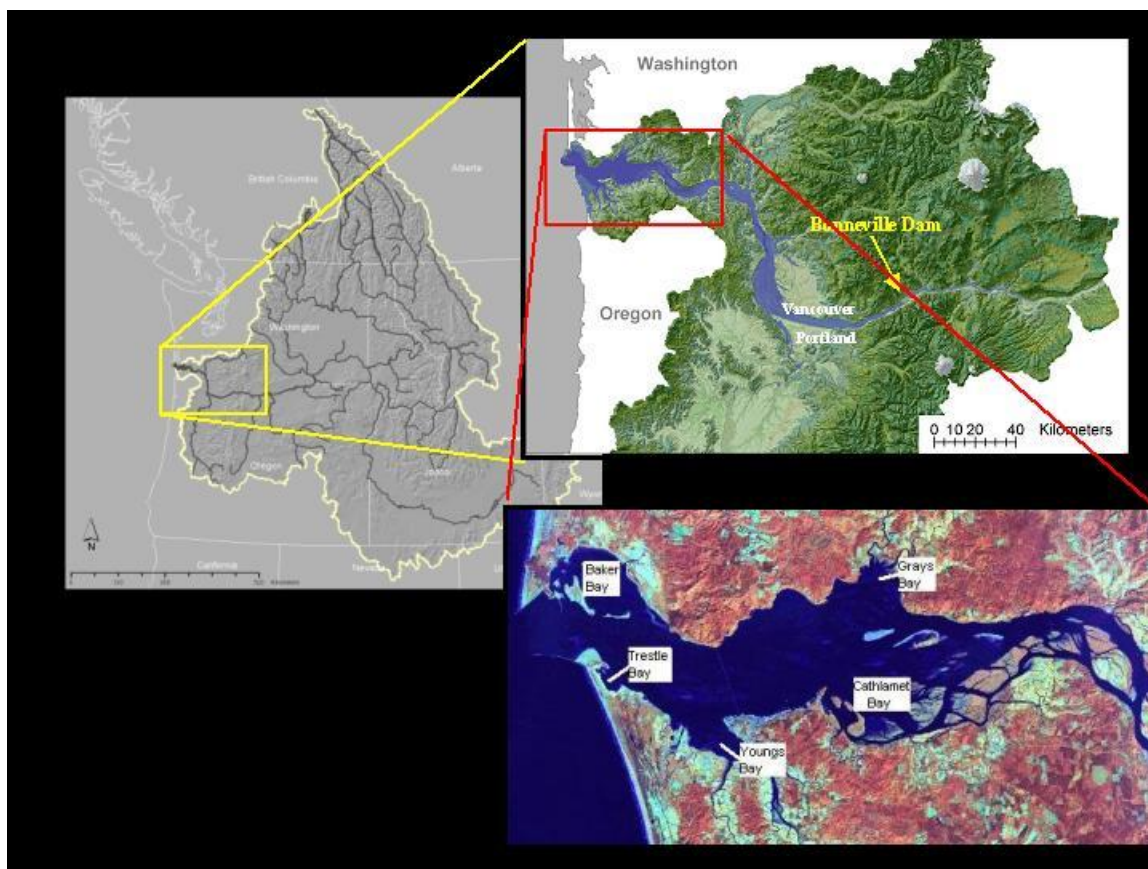
The Columbia River estuary is the gateway to the Pacific Ocean for the second largest river in the United States in terms of discharge, draining an area of 667,000 km<sup>2</sup> (Figure 1) (Fox et al. 1984). Included in this drainage basin are portions of seven states and one Canadian province.

The Columbia drops from an elevation of approximately 800 meters at its origin in British Columbia to about 2.5 meters above sea level at the base of Bonneville Dam at RM-145 (km 233.4) (Fox et al. 1984). Flow in the Columbia River has been highly altered over the past century, as 21 large dams (in addition to hundreds of smaller ones) have been constructed on the Columbia and Snake Rivers since 1933, with the goal of electricity generation, flood control, and reservoir storage of irrigation water for agriculture in the interior Columbia River Basin (Harden 1996, Sherwood et al.

1990). High flow for the Columbia naturally occurred during the summer with the melting of the winter snow-pack in the Cascade Mountains and other mountain ranges associated with the headwaters of the river's tributaries (Harden 1996). With the help of dam control, water is now held back during this freshet, reducing it from natural flows by 50-55% (Sherwood et al. 1990). Instead, the flow of the river has been altered to be highest during the winter months (October through March), when the West's demand for electricity is highest; an increase of 35% over natural flows during this time of year (Harden 1996, Sherwood et al. 1990). Because of these modifications, current river flow is both highly muted (extreme highs and lows have been eliminated) compared to historic flows and also altered in terms of its seasonality.

The estuary itself lies on the border of Oregon and Washington, and is the West Coast's second largest estuary (Figure 1). Some consider the estuary as that portion of the river still experiencing tidal fluctuation, which can extend up to Bonneville dam. But, most studies in the estuary have been focused on the lower Columbia River estuary, up to approximately RM-45 (km 72.4) (Figure 1).





**Figure 1. Columbia River drainage basin, estuary, and lower estuary.**

**Columbia River drainage basin is outlined in the map on the left. Map courtesy of Jen Burke, University of Washington, School of Aquatic and Fishery Sciences. Map layer courtesy of Mindi Sheer, NOAA Fisheries, Montlake, Seattle. Constructed from mosaiced 10m Digital Elevation Models (DEM) from the Regional Ecosystem Office: <http://www.reo.gov/gis/gisdata.htm>.**

**Columbia River estuary is shown in the map in the upper-right. Map courtesy of Jennifer Burke, University of Washington, School of Aquatic and Fishery Sciences. Map layer courtesy of Mindi Sheer, NOAA Fisheries, Montlake, Seattle.**

**Lower estuary is shown in the map on the bottom-right, which encompasses approximately up to River Mile-45 (km 72.4). Prominent bays are labeled. Map courtesy of Jennifer Burke, University of Washington, School of Aquatic and Fishery Sciences. Image is NOAA C-CAP 1992 Imagery.**

The Columbia River estuary is habitat for a plethora of wildlife, including Pacific Northwest salmon such as Chinook, chum, pink, coho, and sockeye (Simenstad et al. 1984, Weitkamp 2001). Its wetlands are important to the rearing of juvenile salmon, particularly Chinook and chum, providing both prey resources (epibenthic prey, planktonic prey, and zooplankton) and protection from predators, thus serving as a transition point on their journey to the Pacific Ocean (Simenstad et al. 2000, Simenstad et al. 1982, Weitkamp 2001). Other fish also reside in the estuary, including white

sturgeon, lamprey, smelt, and American shad. In addition, the estuary provides habitat for countless birds including great blue herons, bald eagles, double-crested cormorants, Caspian terns, diving and dabbling ducks, loons, and Canada geese. Common mammals include river otter, beaver, muskrat, and nutria. Insects and benthic invertebrates, such as Dungeness crab, also abound (Weitkamp 2001).

Given the huge flow of the Columbia River, it is not surprising that its estuary is relatively fresh, making it quite unique among Pacific Northwest estuarine systems (Burg et al. 1976, Disraeli and Fonda 1978, Eilers 1975, Ewing 1983, Fox 1984, Jefferson 1975). In fact, it is only one of four major estuaries along the entire Pacific Coast of North America to receive sufficient outflow of freshwater to support large areas of both brackish and freshwater tidal marshes (Macdonald 1984). The other three examples are the San Francisco Bay-San Joaquin Delta on the central coast of California, the Fraser River delta at the Canadian border, and Cook Inlet in Alaska. Wetlands in the Columbia River estuary are dominated mainly by freshwater plants, with some brackish assemblages near the mouth of the river (within RM-17, km 27.4) (Macdonald 1984, Thomas 1984). Although the brackish water assemblages here can be likened to salt marsh communities common in other bays and estuaries on the coast of Oregon (Eilers 1975, Jefferson 1975), the freshwater tidal assemblages “represent an unique and scarce habitat along the Pacific Coast” (Macdonald 1984).

Before 1980, little was published about the vascular flora of the Columbia River estuary, and information that was available was limited to brief descriptions (Franklin and Dyrness 1973, Jefferson 1974, Thomas 1984). Since then, extensive characterizations of habitats within the estuary, namely those in the lower estuary, have been completed (Macdonald 1984, Thomas 1980, Thomas 1984). Thomas conducted a large-scale study with the Columbia River Taskforce (CREST) in 1980-1982 to characterize wetland vegetation in the first 40 River Miles (64.4 km) of the estuary. He describes seven general vegetation types, comprising marsh, scrub-shrub, and forested wetlands, with varying degrees of tidal influence and salinity (1980, 1984). These included, *brackish marshes below mean higher high water*, *brackish emergent marsh with irregular tidal inundation*, *brackish water scrub-shrub wetland with irregular tidal inundation*, *freshwater emergent marsh with regular tidal inundation*, *freshwater emergent marsh with irregular tidal inundation*, *freshwater scrub-shrub wetlands with irregular tidal inundation*, and *freshwater forested wetlands with irregular tidal inundation* (complete descriptions are given in Appendix B). Macdonald (1984) expanded on Thomas' (1984) work by augmenting a detailed characterization of marsh habitat with an investigation of differences in primary production on an estuary-wide scale. Macdonald (1984) also identified seven vegetation types based on both on his study and that of Thomas (1984). These included, *brackish low marshes*, *brackish high marshes*, *freshwater low marshes*, *freshwater high marshes*, *brackish scrub-shrub wetlands*, *freshwater scrub-shrub wetlands*, and *freshwater forested wetlands*.

Although these vegetation types are quite similar to those described by Thomas (1984), additional species are identified (complete descriptions are given in Appendix C).

Since the arrival of settlers in this area in the 1870's, human activities have influenced the estuary to a huge extent (Thomas 1983, Fox et al. 1984). Those having the largest effect are dike construction, various activities to deepen and maintain navigation channels, dam construction upriver from the estuary with consequential flow alteration, and upriver development (Fox et al. 1984, Jay et al. 1990, Sherwood et al. 1990). These and other activities have led to an average 65% historic loss (as of 1983) of tidal wetland habitat in the Columbia River estuary (Thomas 1983). This is believed to have contributed substantially to recent declines in Pacific Northwest salmon, now with 14 listings on the Endangered Species list, which have been shown to be dependent on estuarine wetlands during their juvenile stages (Simenstad et. al 1982, Simenstad 2000, Weitkamp 2001).

Because of the decline of tidal marshes in the Columbia River estuary, conservation and restoration are essential for rehabilitating and ensuring the continued existence of these habitats and the organisms that they support (Simenstad 2000). While plans and efforts to restore tidal wetlands in the Columbia River estuary are currently underway, their success will depend on how effectively the projects incorporate an understanding of the plant community ecology of these systems. (Marshall et al. 1987, Simenstad 2000).

As described previously, attention has been focused in recent years on characterizing the marshes in the Columbia River estuary (Macdonald 1984, Thomas 1984), while in-depth ecological studies are still lacking. Macdonald's (1984) estuary-wide study of differences in net primary production did address environmental influence, however comparisons were made on a large-scale with only indirect measurements of critical environmental factors. Factors included in his study were: study site distance from the estuary mouth, mean diurnal tidal range, and surface water salinity under both high and low river flow conditions. Although Macdonald (1984) found that surface water salinity and elevation correlated well with net annual aboveground primary production in the tidal marshes, he acknowledges that "the indirect measurements used were a less useful substitute for site specific data than expected". With that, a study that thoroughly investigates plant assemblages with respect to their environmental controls by way of a site-specific investigation has not yet been conducted.

### 1.3 Study Objective

The objective of this study was to fill this gap and to conduct an in-depth, quantitative assessment of the plant community variability at a site representative of the remaining freshwater tidal marsh in the Columbia River estuary, Russian Island, and to investigate environmental and historical

factors that are potentially driving observed community differences. As in all systems, gradation in environmental factors has an enormous impact on the organization of plant communities in Pacific Northwest tidal marshes (Ewing 1986). Elevation (directly related to degree and duration of inundation) and salinity (Burg et al. 1976, Disraeli and Fonda 1978, Eilers 1975, Ewing 1983, Hutchinson 1982, Hutchinson 1988b, Jefferson 1975, Liverman 1981, Taylor 1980) are especially important. Soil texture and organic matter content have also been shown to be influential (Ewing 1983, Hutchinson 1982, Liverman 1981).

Because of their effects on plant community structure found in other estuarine studies, I examined the following factors: elevation, soil texture, soil organic matter content, and soil pore water salinity. I also investigated marsh developmental stage as a potential historical factor affecting the plant community on Russian Island, which was addressed in the selection of sites and through a vegetation community development analysis using Geographic Information System (GIS) technology.

Although the amount of salinity in the Cathlamet Bay area of the Columbia River estuary has been found to be low or non-existent, even slight salinity in soil pore water can greatly influence plant communities (Day 1989). In addition, the observed dominance of *Carex lyngbyei*, a species usually indicative of more brackish conditions, suggested the value of including an investigation of soil pore water salinity in this study.

## 1.4 Hypotheses

Null hypotheses generated were as follows:

1. Elevation does not vary among study sites.
2. Soil texture and organic matter content do not vary among study sites and within study sites.
3. Measurable soil pore water salinity is not present at study sites.
4. If present, soil pore water salinity differences do not exist among study sites and within study sites.
5. Differences in elevation and soil properties does not account for variability in plant assemblages among and within study sites.
6. Developmental stage of marsh does not account for variability in plant assemblages.

## 1.5 Approach for testing hypotheses

The goal of this study was to assess and explain as much of the plant community variability on Russian Island as possible, and, consequently, much thought was given to the scale at which investigations should be focused. Great variability in plant assemblages was observed at the small

scale of individual tidal channels, also the level of resolution at which a UW School of Aquatic and Fishery Sciences salmon habitat study on Russian Island was conducted. The notion of focusing my research at this scale was appealing, given that it would then directly compliment the salmon habitat study. However, differences in the environmental factors of interest were not immediately apparent at this resolution. So, a larger-scale approach was also employed to capture island-wide plant community variability and environmental factor differences. The premise of this approach was that areas of the island of different marsh developmental stage would potentially exhibit different plant assemblages. To start this inquiry, GIS technology was used to compare historic (1870) and current (2000) marsh extents to identify areas on the island of varying developmental stages.

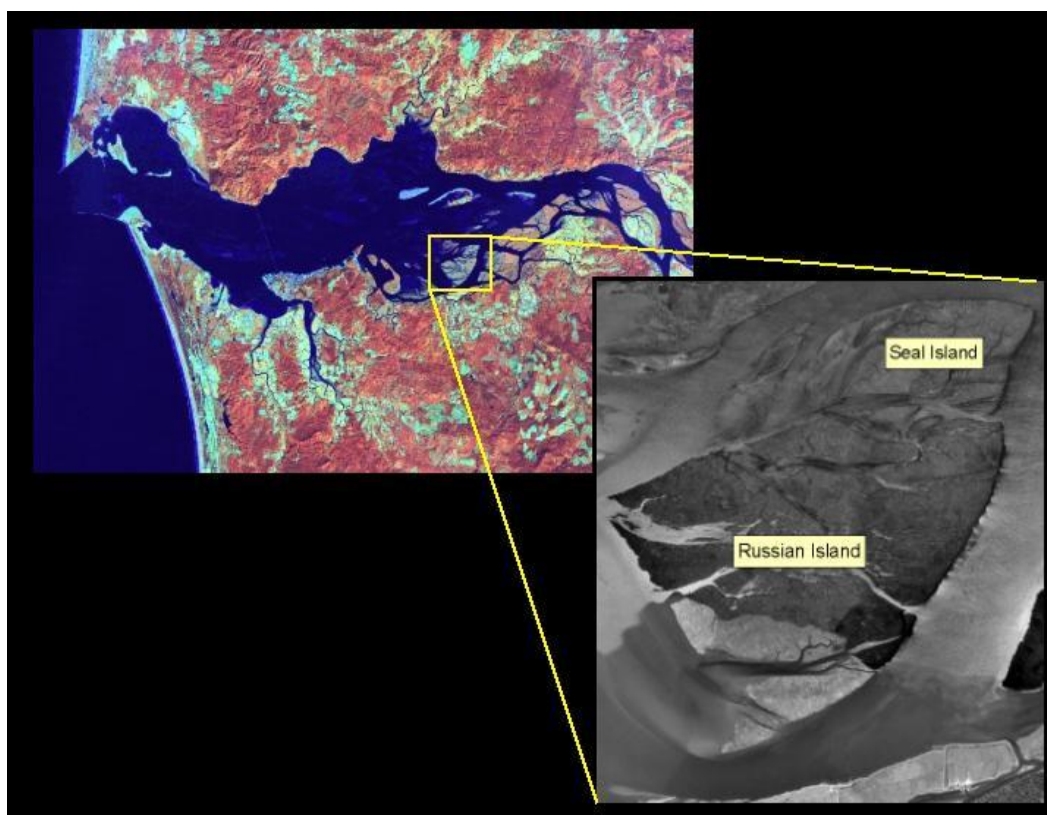
The sampling strategy utilized addressed both small-scale and large-scale variability in the plant community and environmental factors by establishing sites based on developmental stage, and then placing individual sampling stations along a transect at each site to capture variability at the individual tidal channel level. Environmental factors were measured and plant assemblages were assessed at each sampling station at each site. Comparisons of environmental factors among and within sites were accomplished using descriptive statistics, while variability in plant assemblages and relationships to environmental factors was explored using multivariate data analysis. These analytical tools sought to illustrate similar results, just through different techniques.

Finally, on a landscape scale, a remotely sensed image of Russian Island was analyzed and augmented by field knowledge to produce a high-resolution illustration of the entire Russian Island plant community. The assemblages depicted by the image at my individual study sites were then compared to my field study results to open a discussion about the advantages and disadvantages of field and GIS-based research methods. As mentioned, GIS was also used to compare historic and current habitat types on Russian Island to help create an understanding of how the vegetation community on the island has changed since 1870, leading to implications for its potential evolution.

## 2.0 METHODS

### 2.1 Study location: Russian Island

Russian Island is a small (approximately 7 km<sup>2</sup>) marsh island located in Cathlamet Bay, 39 km upriver from the mouth of the Columbia River (RM-24) in the lower estuary (latitude 46° 12', longitude 123° 40') (Figure 2). The island is tidally influenced, with a mean diurnal tidal range of 2.47 m (Macdonald 1984). Average elevation on the island is approximately 2.1 m above mean lower-low water (MLLW). Winters are generally cool and moist, with summers being generally mild and drier. The average annual precipitation in this area is 168.5 cm, with maximum rainfall occurring in December (68.1 cm) and minimum in July (6.2 cm) (Fox et. al 1984). The annual mean daily temperature is 10.3°C (50.5° F), with the warmest month being August (15.7°C, 60.3° F) and the coolest month being January (4.8°C, 40.6° F).



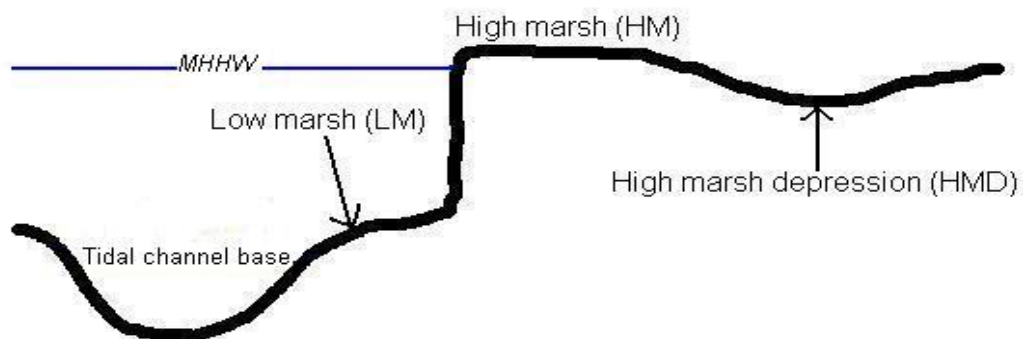
**Figure 2. Russian Island in the lower Columbia River estuary.**

**Lower Columbia River estuary is shown in the map on the left, which encompasses approximately up to River Mile-45 (km 72.4). Map courtesy of Jennifer Burke, University of Washington, School of Aquatic and Fishery Sciences. Image is NOAA C-CAP 1992 Imagery.**

**Russian and Seal Islands are shown in the image on the right, which is a from a digital orthophoto quadrangle from 2000 (State of Oregon 2003).**

Floodwater reaching the surface of the marsh on Russian Island is considered to be virtually fresh (Macdonald 1984). However, at low river flow and neap tide, Fox et al. (1984) illustrated salinity near the river bottom, at the same River Mile as Russian Island (RM-24, kilometer 38.6), to reach almost 20 parts per thousand (ppt). In addition, McConnell et al. (1979) observed salinities near 10 ppt within the upper 10 m of water near the eastern margin of Russian Island. Such salinities occur near Russian Island when water circulation is stratified and salt-water influence penetrates the estuary as a salt wedge. With this, the surface of Russian Island can potentially experience salinity when mixing occurs during spring tide series. Soil pore water salinities in the marsh can also climb higher than floodwater through evaporation and absence of freshwater input for extended periods of time (Mitsch and Gosselink 2000). Russian Island is also characterized by complex (high-order) dendritic channel systems that create a network through the marsh and fill and drain with the tides.

Although, in general, the marsh surface is characterized by only slight changes in elevation (range of about 1 m), a stark difference in plant assemblages can often be observed with elevation heterogeneity associated with the dendritic tidal channels (pers. obs.). In general, as one moves perpendicularly away from a tidal channel, these zones can be described as tidal channel base, low marsh, high marsh, and high marsh depression (Figure 6). These zones should not be confused with Macdonald's (1984) "freshwater low marsh" and "freshwater high marsh" communities (Appendix C).



**Figure 3. Cross-section of representative tidal channel and adjacent marsh.**

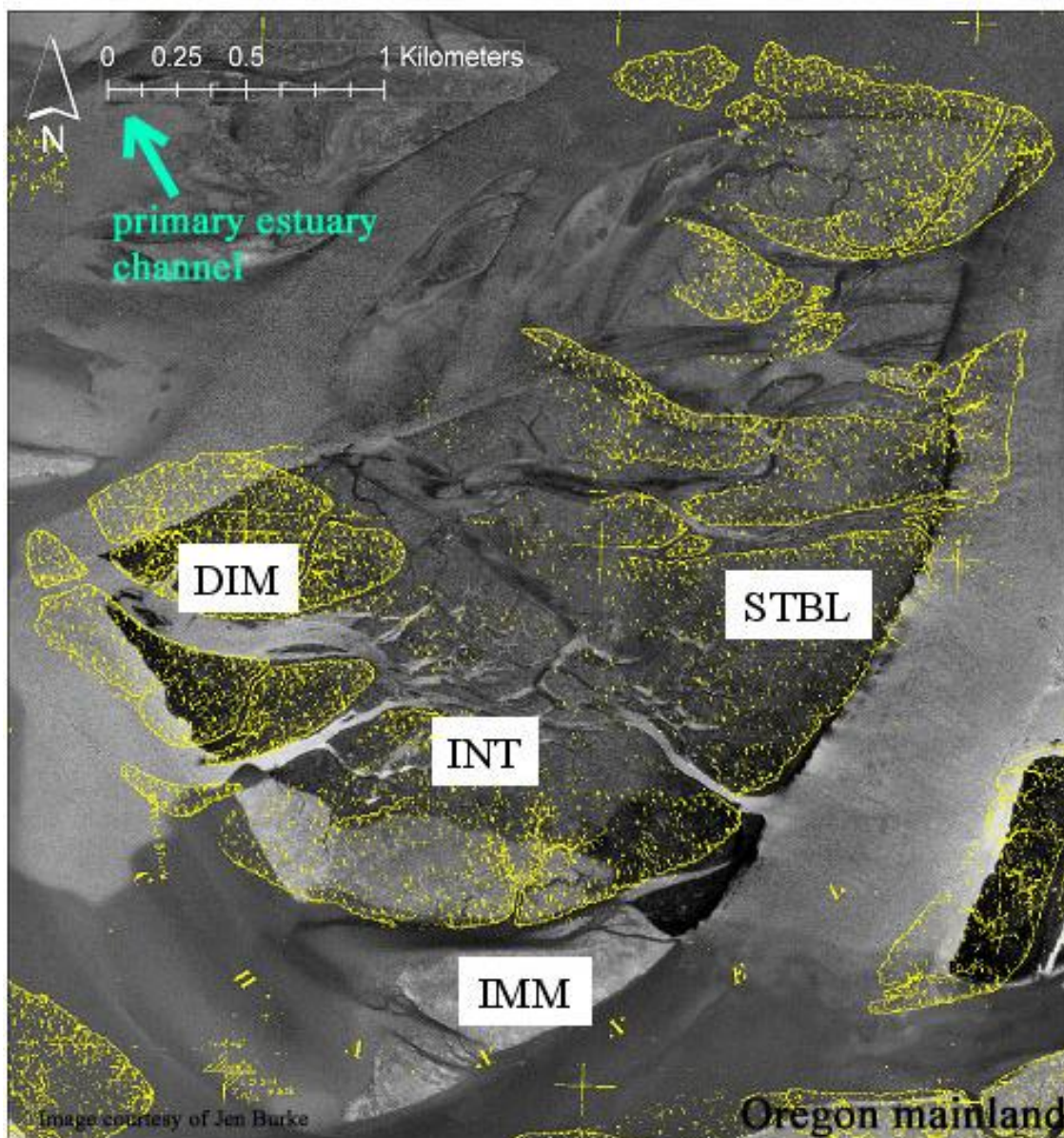
**Low marsh (LM) areas are found directly adjacent to the base of tidal channels and experience the highest frequency and duration of flooding, therefore exhibiting low species diversity and low percent cover. High marsh (HM) areas are inundated less than the LM, are characterized by extremely diverse plant assemblages, and consistently exhibit complete cover during the peak of the growing season. High marsh depressions (HMD) are isolated, lower elevation areas beyond the influence of the levee effect occurring along the banks of the tidal channels. HMDs receive greater inundation than the HM, but less than the LM, and therefore exhibit an intermediate level of diversity and percent cover.**

The general vegetation types found on Russian Island have been characterized, in part, by Thomas (1984) and Macdonald (1984). The prominent type is the high marsh, and it can be described as a combination of Thomas' (1984) *freshwater emergent marsh with regular tidal inundation* and *freshwater emergent marsh with irregular tidal inundation* and Macdonald's (1984) *freshwater low marsh*, *freshwater high marsh*, and *brackish high marsh* assemblages. This is a diverse wetland type and is highly variable in its local species composition (Thomas 1984). It is dominated by *Carex lyngbyei*, with *Juncus oxmyeris*, *Equisetum fluviatile*, *Deschampsia caespitosa*, *Eleocharis palustris*, *Sagittaria latifolia*, *Sium suave*, *Aster subspicatus*, *Lotus corniculatus*, *Potentilla pacifica*, *Caltha asarifolia*, *Agrostis stolonifera*, and *Scirpus tabernaemontani* also being common (Macdonald 1984, Thomas 1984). The low marsh is a vegetation type less common than the high marsh and represents a combination of Macdonald's (1984) *freshwater low marsh* assemblage and the low-salinity extreme of the *brackish low marsh* assemblage. Species found here include *Eleocharis palustris*, *Oenanthe sarmentosa*, *Equisetum* sp., *Scirpus microcarpus*, *Alisma plantago aquatica*, *Callitriche* sp. and *Polygonum hydropiperoides*. The high marsh depression is an assemblage type not called-out by Macdonald (1984) and Thomas (1984) as being separate from the high marsh. Scrub-shrub assemblages, belonging to the vegetation type called *freshwater shrub-dominated wetland with irregular tidal inundation* by Thomas (1984) and *freshwater scrub-shrub wetland* by Macdonald (1984), have a small presence on Russian Island. The only shrub species composing this vegetation type here are members of the *Salix* genus, namely *S. lasiandra* and *S. sitchensis*. Elsewhere in the estuary, this vegetation type comprises a variety of species, such as *Spiraea douglasii* and *Cornus stoloifera* (Macdonald 1984, Thomas 1984).

## 2.2 Study sites

As mentioned, I selected four study sites based on presumed marsh developmental stage, and these were: (1) STBL, (2) IMM, (3) DIM, and (4) INT (Figure 4). The spatial variation in exposure to different erosion and accretion processes (e.g., orientation to main river flow, tidal influence) has led to a distinct and dynamic age stratification of marshes on the island, setting the stage for potential differences in plant assemblages. Presumption of this developmental variation was based on a visual comparison of historical to current marsh extent, using a georeferenced topographic sheet (t-sheet) from 1870 (U.S. Coast and Geodetic Survey), and a current (2000) digital orthophoto quadrangle (DOQ) (State of Oregon 2003).





**Figure 4. Russian Island study sites shown with overlay of 1870 topographic sheet with 2000 digital orthophoto quadrangle.**

The four Russian Island study sites, STBL, IMM, DIM, and INT, are shown in their approximate location. 1870 topographic sheet (U.S. Coast and Geodetic Survey; provided by Jennifer Burke, NOAA Fisheries) [shown in yellow], and a current (2000) digital orthophoto quadrangle (DOQ) (SOR 2003) [black and white] were overlain in ArcMap (ArcGIS, ESRI software) to show historic geomorphic change on Russian Island.

The northeast site (STBL) was chosen because it was on an area of the island that has remained relatively stable over time. It was present in 1870 as high marsh, and has neither increased nor decreased in area since then; therefore, it represents long-term marsh development. In contrast, the site on the south end of the island (IMM) was chosen because it was in an area of marsh that did not exist in 1870, but does exist currently. It is therefore younger and represents short-term marsh development (hence, “immature” site code). The site on the northwest side of the island (DIM) was chosen because it was in a location that appears to have diminished in area over time. The vegetation extent at this part of the island has receded since 1870, most likely caused by erosion due to its close proximity to the primary estuary channel of the Columbia. The site on the interior of the island (INT) was chosen because it is exposed to unique geomorphic processes given its protected location. As high river flow events enter Cathlamet Bay, they first encounter the northern edge of the island complex of which Russian Island is a part. Water then moves across the marsh surface as a sheet flow, carrying sediment across the island. By the time this water reaches the center of the island, its velocity has decreased greatly, and only small-diameter particles remain in suspension. Therefore, the soil of the island’s interior would be expected to exhibit a unique texture compared to soils of the island’s periphery. In addition, given that this area is protected from high velocity river flows and tidal energy, erosion forces are quite small here, and sediment accretion is high. This area was present in 1870 as low marsh, and has since developed into a mosaic of low and high marsh areas. By sampling the four different areas described, I hoped to capture the array of plant assemblage types on Russian Island. Specific study sites were chosen based on constraints on boat access to the island and the limited timeframe available dictated by tidal influence on water depth in the channels used for access.

## 2.3 Sampling stations

One transect (~30 m) at each study site was established perpendicular to the main access channel to consistently capture small-scale variability in plant assemblages associated with the micro-topographic variation moving inland from the channel edge (Figure 3). Sampling stations were placed non-randomly along the transect in locations characterized by distinct vegetation assemblages and/or a noticeable elevation difference (Table 1). STBL, DIM, and INT marsh sites had four sampling stations each, while the IMM marsh site had three sampling stations (due to a less heterogeneous association of plants). Because the study sites were only accessible at high tide, I could not as frequently sample low marsh locations, but a low marsh area at the INT site was able to be sampled during two trips.

**Table 1. General descriptions of sampling stations at Russian Island study sites.**

Site	Sampling station	Approx. distance from access channel (m)	Elevation (m above MLLW)	General description (see Figure 3)
IMM	1	5	1.9	in between LM and HM
	2	15	2.0	in between LM and HM; <i>Phalaris arundinacea</i> patch
	3	25	1.9	in between LM and HM; <i>Lythrum salicaria</i> patch
INT	1	0.5	1.6	LM
	2	3	2.2	HM
	3	15	2.3	HMD
	4	30	2.3	HM; small <i>Salix</i> component
DIM	1	2	2.2	HM (hummock-hollow topography)
	2	10	1.8	HMD
	3	20	2.2	HM; small <i>Salix</i> component
	4	30	2.3	HM; <i>Typha latifolia</i> stand
STBL	1	2	2.4	HM
	2	10	2.4	HM
	3	20	2.5	HM; <i>Phalaris arundinacea</i> patch
	4	30	2.6	scrub-shrub; large <i>Salix</i> stand

Study sites and sampling stations were marked with bamboo poles and flagging and their locations were recorded with a handheld Magellan Meridian Marine GPS receiver (Thales Navigation, Inc.). They were re-located for sampling on subsequent trips using both the GPS and the poles. Sites were established on May 8, 2003 and revisited at the beginning of June, July, and August 2003.

## 2.4 Data collection

### 2.4.1 Elevation

Elevation (in international ft above mean lower low water (MLLW)) at each sampling station at each site was determined to 2.5 cm accuracy using a Trimble 5800 RTK GPS Surveying System (Trimble Navigation Limited, 749 North Mary Avenue, Sunnyvale, CA 94088-3642) in August 2003. Measurements in international feet were converted to metric units for report purposes.

### 2.4.2 Soil texture and organic matter content

Soil samples were collected at each sampling station on each trip in a consistent location from the upper 15 cm of soil. Soil samples were immediately sealed in Ziplock<sup>®</sup> bags and stored in a cool

location until analysis. Because of time constraints on site accessibility due to tidal influence on water depth in channels, INT1 was only sampled twice.

Soil texture at each site was quantitatively assessed in the lab using a hydrometer-based grain size analysis technique consistent with Gee and Bauder (1986) and with methodology from Gayaldo (2002). In addition, soil organic matter was determined during the process of preparing the soil for texture analysis. Soil samples for each month were analyzed separately as replicates to ensure accuracy.

Soil samples were first dried in a drying oven at 105°C for 24 hr, and were then transferred to a muffle furnace (NEY Dental International A-550 Furnace; Yucaipa, CA), where they were burned for four hr at 550°C. Subtraction of post-burn sample weights from pre-burn weights was used to estimate organic matter content (Gee and Bauder 1986).

Soil samples of consistent weight (40g) were added to 500mL Erlenmeyer flasks containing a 50 g L<sup>-1</sup> sodium hexametaphosphate (anti-flocculant) solution. Samples were then crushed and shaken to homogenize the suspension and were transferred to 1000 ml graduated cylinders, where de-ionized water was then added to achieve exactly 1000 ml. Hydrometer readings were taken at 30 s, 1 min, 1.5 hr, and 24 hr after initial mixing with a VWR ASTM Soil Hydrometer [152 H temp. 20°C #75086 (units = g L<sup>-1</sup>, Bouyoucos scale)]. Temperature readings were also taken at the same time intervals using an Omega digital thermometer (HH81A) and a type “T” thermocouple. Hydrometer results were used in a series of equations that relate the diameter of particles to the rate at which they fall out of suspension to achieve sand, silt and clay percentages (Gayaldo 2002). Equations used in grain size analysis calculations are given in Appendix D.

### 2.4.3 Soil pore water salinity

Soil samples for salinity measurements were taken from each sampling station on each trip in a consistent location using a 3.8 cm diameter corer that was 15 cm in length. As much as possible, surface debris, organic matter, and rhizomatous matting were removed before the soil core was taken. Although the soil cores varied in length upon extraction, they were extruded onto a tray where they were cut to a length of exactly 7.62 cm, so that a consistent soil volume of 86.87 ml was achieved. Samples were sealed in Ziplock<sup>®</sup> bags and stored in a cool, dry location until analysis. Because of time constraints on site accessibility due to tidal influence on water depth in channels, INT1 was only sampled twice.

In the lab, cores were removed from Ziplock<sup>®</sup> bags and immediately weighed to determine their wet weight. All samples were then dried at 105°C in a drying oven until constant weight, and

then reweighed. Cores were then placed in sealable jars with twice their volume of deionized water, and soil aggregates were crushed and jars were shaken vigorously to homogenize/suspend all soil to facilitate salt extraction. Samples were shaken periodically over the following three days, and were stored in the cold room (2°C) to settle for another three days. 50 ml of the resulting clear supernatant was then extracted from each sample using a graduated pipet and placed in vials for transport. Osmolality of the soil extract was then measured with a freezing point depression osmometer (Advanced™ Micro Osmometer Model 3300, Advanced Instruments, Inc., Lab products division, Two Technology Way, Norwood, Massachusetts 02062, USA). Duplicate runs were performed for each sample, and if results differed, a third run was performed and the results averaged to achieve a consistent value for the sample. From this value for osmolality of the soil extract, the following two additional values were calculated: (1) the osmotically active solutes per unit volume of soil ("a" below) in  $\text{mOsm cm}^{-3}$  and (2) the apparent osmolality of the soil solution at the time of the sample was taken ("e" below) in  $\text{mOsm g}^{-1}$  water (Mahall and Park 1976). These two values were calculated as follows:

$$a = (b \cdot c) / d$$

$$e = (b \cdot c) / f$$

a = osmotically active solutes per unit volume of soil ( $\text{mOsm ml}^{-1}$ )

b = osmolality ( $\text{mOsm ml}^{-1}$  water same as  $\text{mOsm g}^{-1}$  water) of soil extract  
(from freezing point depression)

c = volume of water added to dry soil core (ml)

d = original volume of soil core (ml)

e = apparent salinity of soil solution ( $\text{mOsm g}^{-1}$  water)

f = weight of water in soil core from drying (g)

Finally, the approximate salinity in parts per thousand (ppt) of soil solution was then determined by dividing the apparent osmolality of soil solution (e) by 0.029 (Ewing and Kershaw 1986).

#### 2.4.4 Vegetation assemblages

Quantitative vegetation community assessment was conducted in July 2003, when most plants on Russian Island were in flower, using presence/absence method. Six  $1\text{-m}^2$  non-grid quadrats (only five quadrats for each sampling station were possible at the INT site due to access time

limitations) were haphazardly placed at each sampling station, and all plant species present were recorded. Nomenclature followed Hitchcock and Cronquist (1976) with recent changes from USDA, NRCS (2004).

#### 2.4.5 Data preparation for multivariate analysis

Vegetation presence/absence data were entered into a Microsoft Excel<sup>®</sup> spreadsheet. A separate spreadsheet comprising the collected environmental data was also constructed. It included sand, silt, and clay percentages (averaged for May, June, July, August), soil pore water salinities (May, June, July, August), elevation, organic matter, and developmental stage (STBL = 4, DIM = 3, INT = 2, IMM = 1) of each site. Because soil samples were unable to be collected from INT1 in July and August, soil pore salinities for quadrats at this sampling station were entered as the average of the soil pore salinities measured at INT2, INT3, and INT4. I felt this solution was justified given that patterns of within-site variability in soil pore salinity were not apparent. Excel spreadsheets were then converted to a WK1 (Lotus 1-2-3) file and formatting requirements for PC-ORD were executed.

### 2.5 Data analysis

#### 2.5.1 Descriptive statistics

Quantitative environmental factor data were compared among study sites using descriptive statistics. Data for elevation, soil pore water salinity (May, June, July, and August), soil texture (% sand, % silt, % clay averaged over the four months), and organic matter content at each sampling station were entered into Microsoft Excel<sup>®</sup> spreadsheets separate from those used for the multivariate analysis. Graphs were constructed using individual sampling station values as well as site averages to visually depict within and among-site differences. Analysis of variance (ANOVA) was not used because sampling methods didn't comply with required assumptions (e.g., normal data, randomization) (Zar 1999).

#### 2.5.2 Diversity comparisons

The importance of plant community diversity and its evaluation is a widely discussed topic, but most researchers agree that ecosystems characterized by high diversity are more resilient to stochastic events and exhibit more habitat value than low-diversity ecosystems (Barbour et al. 1999). Many restoration and conservation efforts are also designed with a diversity-based goal in mind (Barbour et al. 1999). Whittaker (1972) proposes three types of diversity: gamma ( $\gamma$ ), alpha ( $\alpha$ ), and

beta ( $\beta$ ). Gamma diversity is a measure of diversity at the landscape level, which is defined as simply total species richness across all sites (Whittaker 1972). Alpha diversity refers to diversity in individual sample units, and is often related simply in terms of species richness (McCune and Grace 2002). However, this measure fails to address inequalities in relative abundances of species or equitability in distribution of species (evenness). Therefore, Whittaker (1972) suggests using a direct diversity expression (species richness) in addition to a measure that incorporates equitability (evenness) for conveying alpha diversity. I accomplished this by reporting species richness, as well as an illustration of evenness using Pielou's  $J$  (Pielou 1969), and the Shannon Diversity Index (Shannon 1948). Equations used in diversity calculations are given in Appendix F.

### 2.5.3 Multivariate analysis

Multivariate analyses are exploratory techniques that enable the researcher to visualize the variation in plant assemblages on the basis of their similarities and dissimilarities in terms of species composition. The way in which the plant associations segregate in the analyses allows the researcher to infer environmental conditions that distinguish those assemblages in the field.

Collected floristic and environmental factor data were analyzed using the multivariate software package, PC-ORD version 4.20 (McCune and Mefford 1999). The main matrix comprised species presence-absence data for each quadrat (47 species and 86 quadrats) and the second matrix contained environmental data (elevation, %sand, %silt, %clay, May salinity, June salinity, July salinity, August salinity, organic matter, and developmental stage) for each quadrat. Gamma diversity (total species richness across sites) and alpha diversity (species richness per site) were also calculated (Whittaker 1972). PC-ORD was used to perform ordinations using Detrended Correspondence Analysis (DCA) and classification of plant assemblages using Two-way Indicator Species Analysis (TWINSpan) (Gauch and Whittaker 1981, Hill 1979, Hill and Gauch 1980, Jongman et al. 1995, Kent and Coker 1992, McCune and Grace 2002). Joint plots, vectors that represent measured environmental factor gradients, were overlain on the ordination to assist in the interpretation of their role in driving the variation in vegetation assemblages. TWINSpan results were also imposed on the ordination to visualize clustering of species and plots into distinct groups, providing further insight into the organization of plant associations related to environmental controls.

## 3.0 RESULTS

### 3.1 Environmental factors

#### 3.1.1 Elevation

The average elevation of the four sites on Russian Island was 2.2 m above MLLW, but varied among sites and within sites (micro-topographic differences) (Figure 5). The STBL site had the highest elevation, with an average across sampling stations of approximately 2.5 m. In contrast, the IMM site had the lowest elevation, with an average of approximately 1.9 m. The DIM and INT sites had similar elevations of about 2.1, but with notably lower values occurring at sampling stations located in the LM and in a HMD. Mean higher-high water (MHHW) was 2.47 m, and so that none of the study areas were free from frequent inundation.

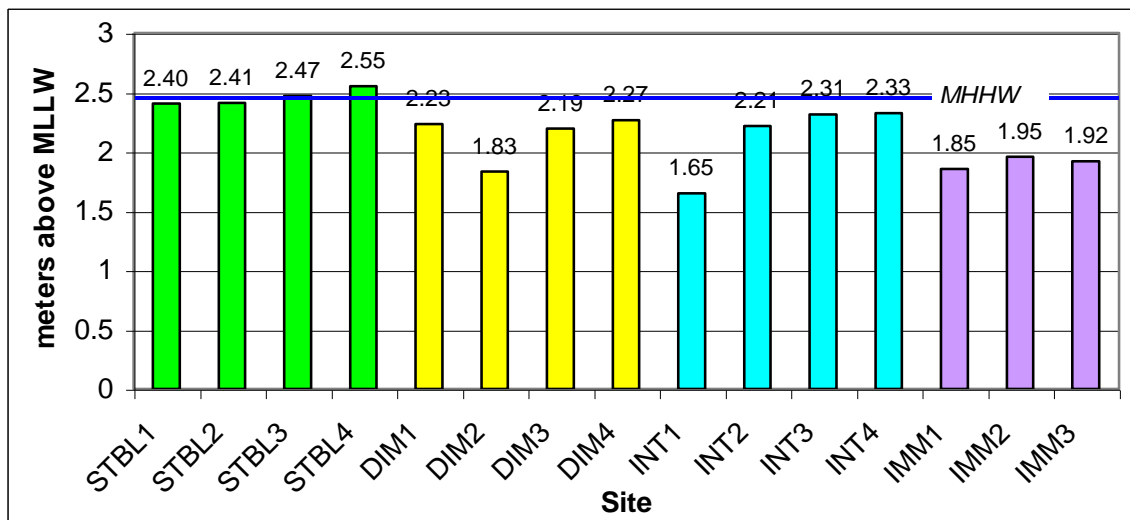


Figure 5. Elevation in meters above MLLW of sampling stations at Russian Island study sites.

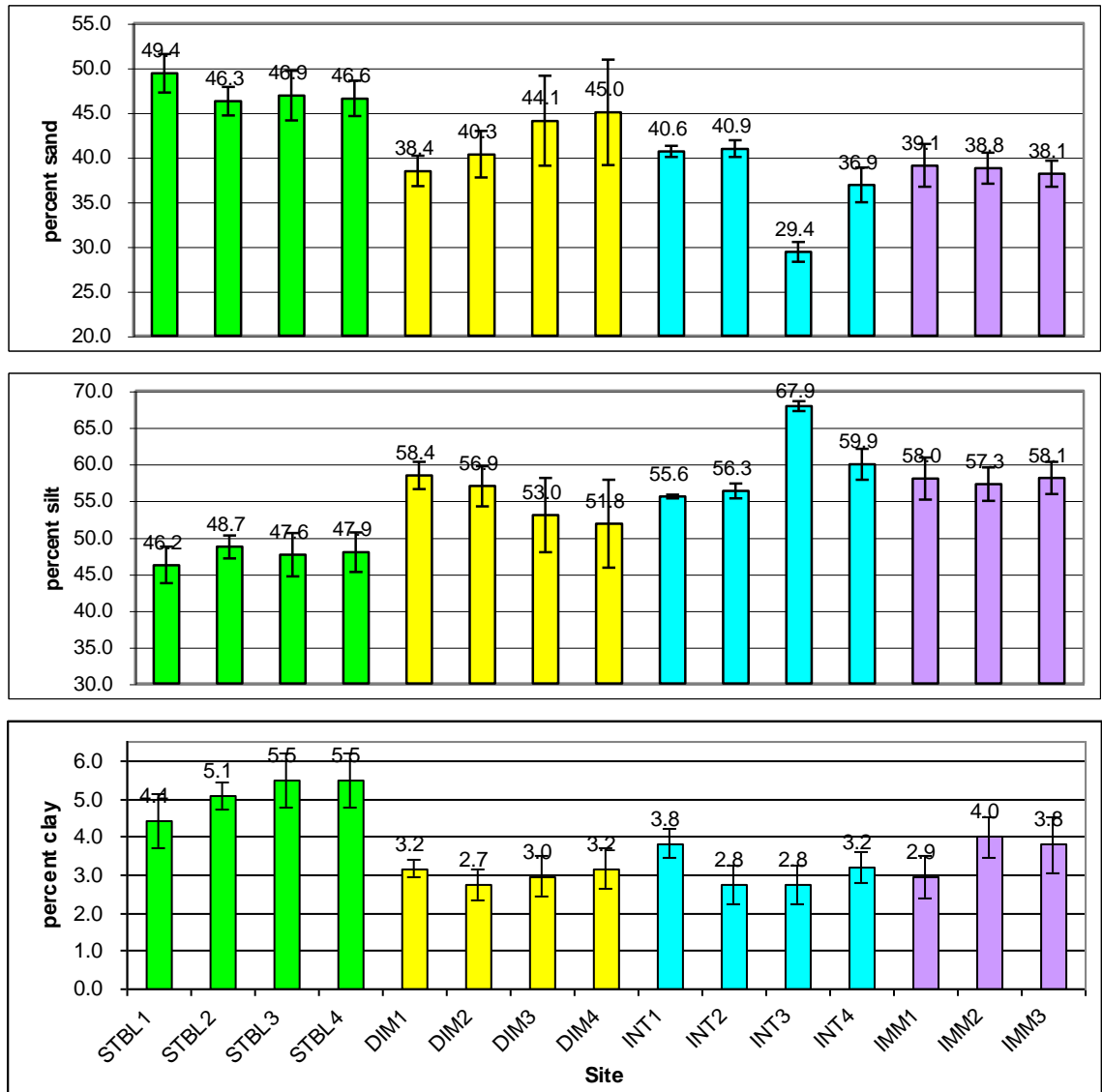
Mean higher high water (MHHW) mark indicates the average height of the higher of the two daily high tides observed over a specific time interval as given by Macdonald 1984.

#### 3.1.2 Soil texture

The grain size analysis showed that the sand (0.05mm to 2.0mm diameter) content of soils at the four sites on Russian Island varied from 29.4% to 49.4% (Figure 6). On average, the STBL site had the highest sand content, at about 47%. The INT site had the lowest average sand content, at about 37%, namely due to the extremely low value at the INT3 sampling station, which was located in a HMD. Silt (0.05mm to 0.002mm) content of soils at the four sites varied from 46.2% to 67.9% (Figure 6). The INT site had the highest average silt content, at about 60%, namely due to the



extremely high value at the INT3 sampling station, which was located in a HMD. The STBL site had the lowest average silt content of all the sites, at about 48%. Clay (smaller than 0.002mm) content of soils of the four sites varied from 2.7% to 5.5% (Figure 6). It was highest at the STBL site, at about 5%, with the other sites having similar, lower soil clay content averages, at about 3-3.5%.

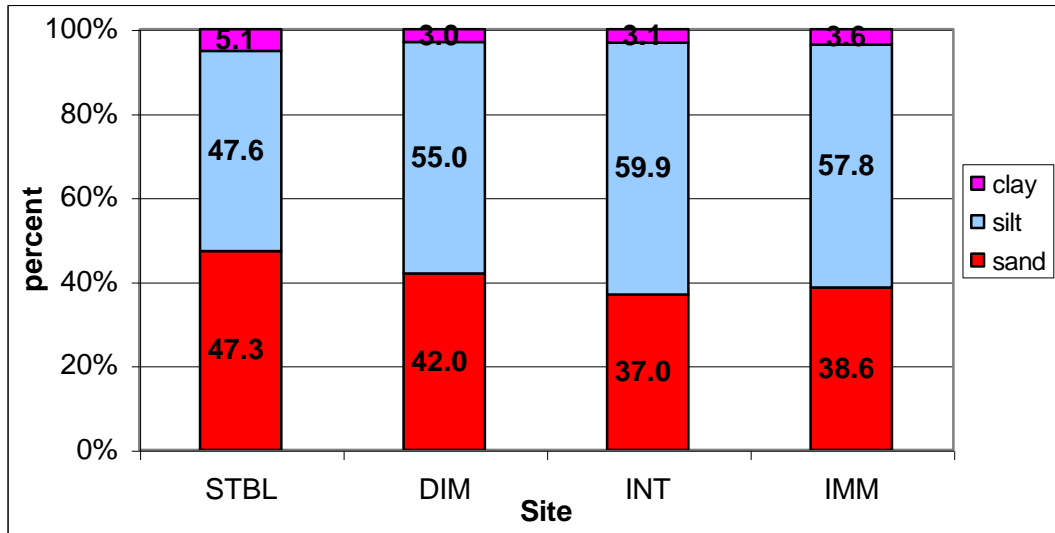


**Figure 6. Sand, silt, and clay content of soil from Russian Island study site sampling stations.**

**Averages for the months of May, June, July, and August at each sampling station at each site (STBL, DIM, INT, and IMM) as determined by grain size analysis. Error bars show +/- 1.0 standard errors for means of months at each sampling station.**

In summary, the STBL site had the highest sand and clay percentages, while having the lowest silt content. It also exhibited the most even distribution of the three soil texture components

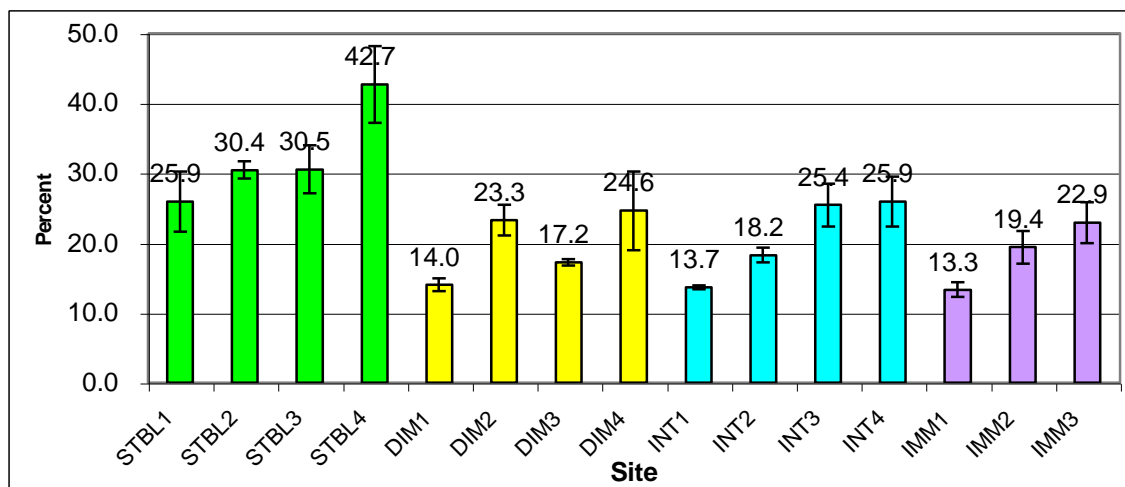
(Figure 7). The INT site had the highest silt percentages and the lowest sand content, with the IMM site was a close second. Greatest within site differences were characterized by low sand content and high silt content in the HMD.



**Figure 7. Summation of sand, silt, and clay content averages of soil from Russian Island study sites.**

### 3.1.3 Organic matter content

Average organic matter content across all four Russian Island sites was 23%, but varied greatly among and within sites (Figure 8). Organic matter was highest at the STBL site, which had an average of slightly above 30%, while the other three sites (DIM, INT, and IMM) had similar organic matter contents averaging about 20%. Also apparent is the general trend of increasing organic matter content with increasing distance from the access channel at each site, with a strikingly high value found at STBL4, the only sampling station in the study located in a *Salix* stand.

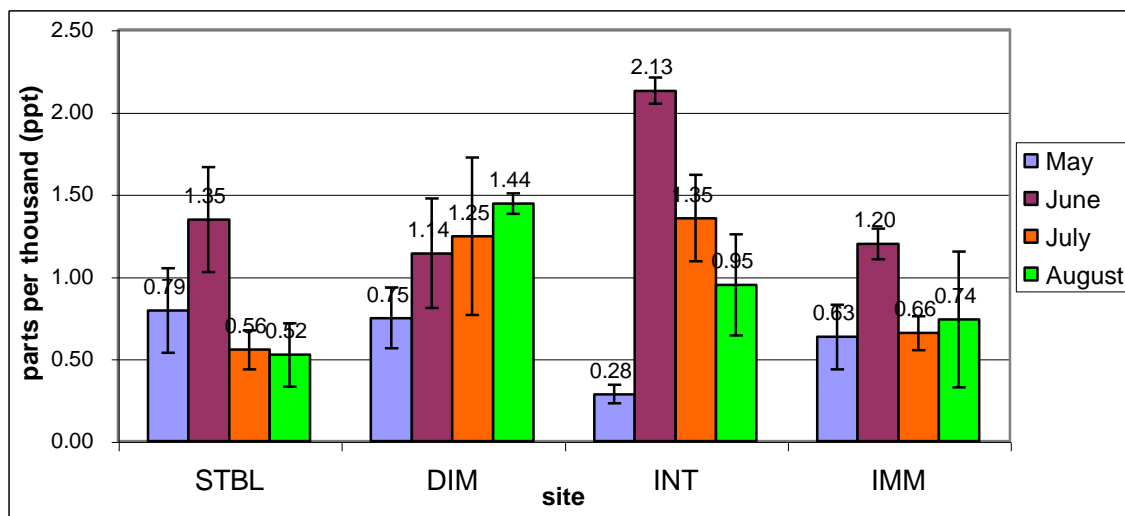


**Figure 8. Organic matter content of soil from sampling stations at Russian Island study sites.**

**Averages for the months of May, June, July, and August at each sampling station as determined by grain size analysis. Error bars show +/- 1.0 standard errors for means of months at each sampling station.**

### 3.1.4 Soil pore water salinity

Slight salinity was found in the pore water of soil samples from Russian Island study sites, although it was extremely low, with a maximum of 2.60 ppt (Figure 9). The average soil pore water salinity across all four sites was found to be lowest during May (0.61ppt) and highest during June (1.46ppt). Soil pore salinity was similar in July and August, at about 0.9 ppt. No consistent among or within-site trends were observed, but graphs depicting soil pore salinity at each sampling station for each month are given in Appendix G.



**Figure 9.** Average soil pore water salinity of Russian Island study sites.

Averages across sampling stations from each site are shown with error bars denoting  $\pm 1.0$  standard errors.

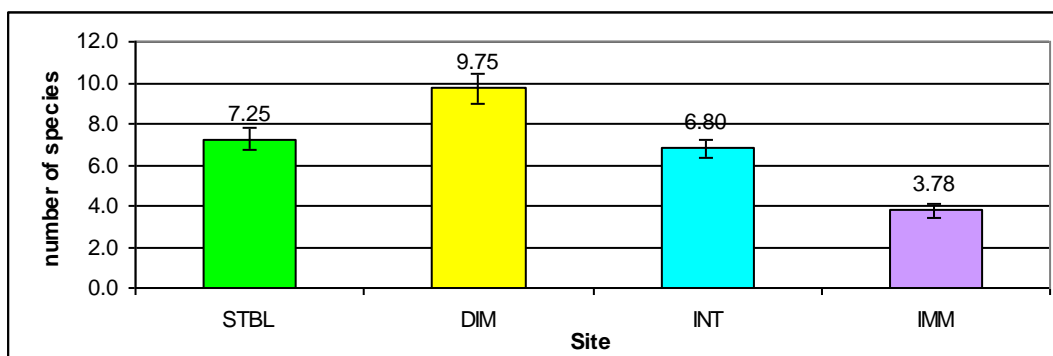
## 3.2 Plant assemblages

### 3.2.1 Vegetation assessment summary

47 plant species belonging to 28 families were found within the 86 quadrats sampled at the four sites on Russian Island. Most of them were herbaceous perennials, with the occurrence of only two woody species (both *Salix* sp.). *Carex lyngbyei* generally dominated the sampling areas, with *Deschampsia caespitosa*, *Equisetum fluviatile*, *Juncus oxymersis*, *Mimulus guttatus*, *Myosotis laxa*, and *Potentilla pacifica* also being common. A number of species considered rare in this area of the Pacific Northwest were also found, including *Sagittaria latifolia*, *Caltha palustris*, *Epipactis gigantea*, and *Platanthera dilata*. Non-native invasive plant species were also sampled, with *Phalaris arundinacea* occurring most frequently and *Lythrum salicaria* also being common. Others non-natives included, *Iris pseudacorus*, *Lotus corniculatus*, *Rubus discolor*, *Solanum dulcamara*, *Festuca arundinacea*, *Hieracium* sp., and *Poa trivialis*. A complete list of plant species surveyed in the study with family, species code, wetland indicator status, salt tolerance, general Pacific Northwest Habitat, and Russian Island habitat is given in Appendix H.

### 3.2.2 Diversity comparisons

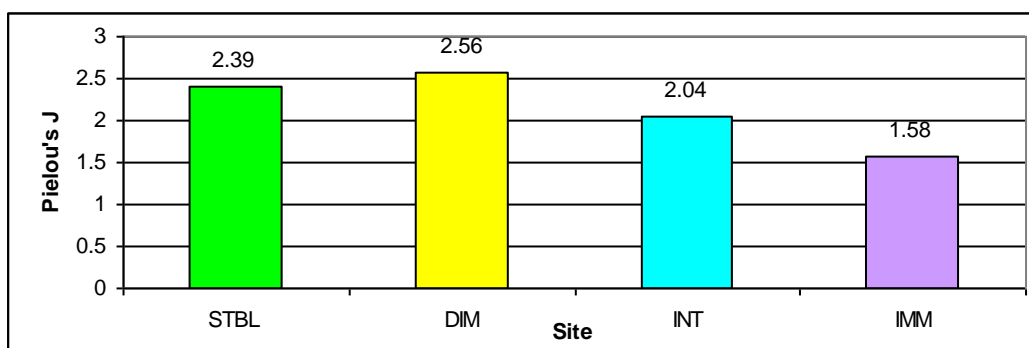
The average sample unit had 7.1 species, but ranged from 3 species to 17 species and varied greatly by site (Figure 10). The DIM site exhibited the highest species richness at 9.75 average species per quadrat, while the IMM site had the lowest at 3.78 species per quadrat.



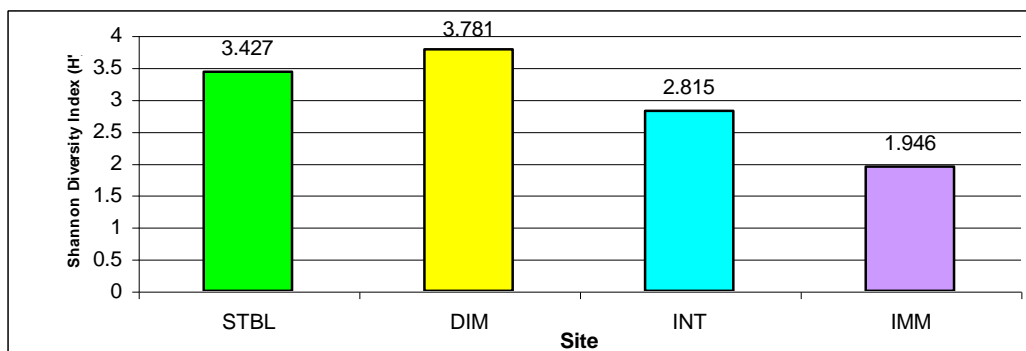
**Figure 10. Average species richness at Russian Island study sites.**

Averages across sampling stations from each site are shown with error bars denoting  $\pm 1.0$  standard errors.

Evenness of species distribution, as represented by Pielou's  $J$  in Figure 11, averaged 2.14 across sites, while the Shannon Diversity Index average for all sites was 1.846 (Figure 12). The DIM site had the highest Pielou's  $J$  value and the highest Shannon Diversity Index value, while the IMM site had the lowest value of both measures. In summary, the DIM site had the highest plant species diversity, followed by the STBL site, and the IMM site had the lowest plant species diversity, followed by the INT site.



**Figure 11. Evenness in species distribution (as represented by Pielou's  $J$ ) across quadrats at Russian Island study sites.**



**Figure 12. Shannon Diversity Index at Russian Island sites.**

### 3.2.2 Classification using TWINSpan

TWINSpan is a widely used classification technique that simultaneously classifies species and quadrats (referred to as “plots” or “stands”) and distinguishes assemblages on the basis of species co-occurrence (Gauch and Whittaker 1981, Hill 1979, Jongman et al. 1995, Kent and Coker 1992). This analysis iteratively divides plots into groups representing greater refinement in similarity of species composition until the researcher determines that the divisions are no longer resulting in ecologically meaningful groups (Gauch 1982, Kent and Coker 1992). Examination of these groups of plots, and the tolerances of the species that define them, then allows the researcher to make inferences about the environmental factors distinguishing the assemblages. Eigenvalues are given for each division, indicating the degree of difference between the created groups. The resulting groups can then be projected onto the DCA ordination to further aid in the visualization of species assemblages in relation to each other and the underlying environmental gradients.

A classification dendrogram displaying groupings of plots was also created from the TWINSpan output (Figure 13). I chose to interpret the five groups of stands depicted because they generally comprised plots and species occurring at similar elevations and/or sites of similar developmental stage, as observed on field visits to Russian Island. The following section describes each division and the subsequent groups with regard to their diagnostic elevation characteristics and plant species.

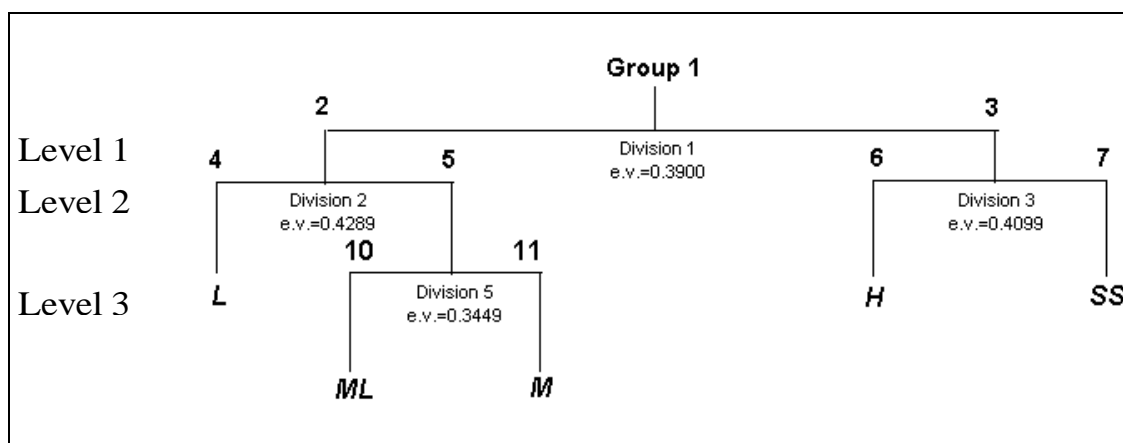


Figure 13. TWINSpan classification dendrogram.

Group 1 comprised all of the quadrats/plots sampled in the study. The intermediary groups are denoted as numbers, and the resulting final five groups are shown by their codes (L=low, ML=mid-low, M=mid, H=high, SS=scrub-shrub). The importance of each division of plots is numerically represented as an eigenvalue (e.v.).

The first division (Level 1) separated mid to low elevation vegetation (Group 2) from the higher elevation vegetation (Group 3) (Figure 13). A moderate eigenvalue (0.3900) is associated with this first level of division, indicating reasonable clustering of the groups. Group 2, lower elevation vegetation, is characterized in part by *Carex lyngbyei*, *Deschampsia caespitosa*, *Juncus oxymetris*, *Oenanthe sarmentosa*, and *Polygonum hydropiperoides*. Group 3, higher elevation vegetation, is characterized in part by *Salix sitchensis*, *Juncus effusus*, *Impatiens noli-tangere*, *Lysichiton americanus*, and *Festuca arundinacea*.

The second division (Level 2) divided stands in the lower elevation group (Group 2) into two groups: those mostly occurring at the least developed sites and the lowest elevations (Group 4), and those mostly occurring at low to mid elevations at all sites (Group 5) (Figure 13). A relatively high eigenvalue (0.4289) is associated with this second division, indicating a better clustering of the groups. Diagnostic species of Group 4, or the “Low” group, are *Callitriche* sp., *Scirpus tabernaemontani*, *Scirpus microcarpus*, *Eleocharis palustris*, and *Lilaeopsis occidentalis*. All of the stands in this subgroup are found at low elevation areas of the study: sites of earlier developmental stage (IMM and INT), in the low marsh (INT1), and in high marsh depressions (NW2). With 24 plots, this subgroup was the second largest in the study. Group 5 is characterized in part by *Carex lyngbyei*, *Deschampsia caespitosa*, *Typha latifolia*, *Mentha arvensis*, *Mimulus guttatus*, *Aster* sp., and *Lupinus polyphyllus*. The stands in this subgroup occurred at low to mid elevations at all sites.

Also at Level 2, the third division divided stands in the higher elevation group (Group 3) into two groups: those mostly occurring at sites of later developmental stage at mid elevations (Group 6),

and those occurring only at the STBL site at the highest elevations (Group 7) (Figure 13). A fairly high eigenvalue (0.4099) is associated with this third division, indicating relatively good clustering of groups. Diagnostic species of Group 6, or the “High” group, are *Lysichiton americanus*, *Iris pseudacorus*, *Hypericum anagalloides*, and *Impatiens noli-tangere*. With 20 plots, this subgroup is the third largest in the study, and its stands are found mostly at the STBL site (everywhere but the highest elevations), but also have slight occurrences at the INT site (one plot) and the IMM site (two plots) at the higher elevations. Diagnostic species of Group 7, the “Scrub-shrub” group, are *Salix sitchensis*, *Rubus discolor*, *Festuca arundinacea*, and *Athyrium filix-femina*. With five plots, this is the smallest subgroup in the study. All of the stands in this subgroup are found in and around the fairly extensive *Salix* stand, occurring at the STBL site at the highest elevations (STBL4 sampling station).

The fifth division (Level 3) divided stands occurring mostly at low to mid elevations at all sites (Group 5) into two groups: those occurring at the INT site at mid-low to mid elevations (Group 10), and those occurring at mid elevations at most sites (Group 11) (Figure 13). A moderate eigenvalue (0.3449) is associated with this fifth division, indicating reasonable clustering of groups. Diagnostic species of Group 10, the “Mid-low” group, are *Carex lyngbyei*, *Oenanthe sarmentosa*, *Sagittaria latifolia*, *Juncus oxymiris*, *Caltha palustris*, and *Polygonum hydropiperoides*. This subgroup is the second smallest (10 plots) in the study, and its stands are found only at the INT site, in the low marsh and in the high marsh, but not in the HMD. Species diagnostic of Group 11, the “Mid” group, are *Carex lyngbyei*, *Deschampsia caespitosa*, *Mentha arvensis*, *Mimulus guttatus*, *Hieracium* sp., and *Typha latifolia*. With 27 plots, this subgroup was the largest in the study, and its stands were located at the mid-elevation high-marsh at all of the sites except INT.

Some species were ubiquitous in this study, thereby not characterizing any particular group. These included *Myosotis laxa*, *Equisetum fluviatile*, *Phalaris arundinacea*, and *Lythrum salicaria*, with *Myosotis laxa* and *Equisetum fluviatile* being quite common. *Phalaris arundinacea* was common except in the M and ML groups, and both *Phalaris arundinacea* and *Lythrum salicaria* were often locally abundant when present, tending to create monocultures and exclude other species.

The Two-way Ordered Table is another powerful result of the TWINSpan analysis, which arranges species on the basis of their similarities in occurrence, with species found on either end of the list occurring in very different environments from each other. A constructed summary of the table is given in Appendix 78; species occurring on the top of the list are found at lower elevation sites, and those occurring at the bottom of the list are found at higher elevation sites. Their frequency of occurrence in each of the five TWINSpan classes is also shown.



### 3.2.3 Ordination using DCA

DCA is a widely used ordination technique that arranges plots and species on a graph in locations that are based on their ecological similarity (Jongman et al. 1995, Kent and Coker 1992, McCune and Grace 2002). The distances among plot points on the graph are a representation of their similarity in terms of species composition (thus, plots exhibiting exactly the same species in the same abundances would occupy the same point on the diagram), while distances among species points are an approximation of their similarity in terms of distribution within the plots (thus, species occurring with exactly the same abundances in the same quadrats would occupy the same point on the diagram). As mentioned previously, the assumption is made in this analysis that the variation in floristics will inevitably reflect variation in the environment, so plots and species found in the same locations on the graph tend to be found in similar environments in the field.

The axes of the ordination graph represent underlying environmental controls causing these similarities or dissimilarities in plant assemblages and are arranged in decreasing order of importance, with the first axis explaining more variation than the second, and so on (Jongman et al. 1995, Kent and Coker 1992). Overlays of vectors representing measured environmental factor gradients can further aid the interpretation of species-environment relationships. Eigenvalues are a numeric representation of the relative contribution by each axis to the explanation of the total variation in the data. In this way, the size of the eigenvalue for a given axis is a direct indication of the importance of that axis (and the environmental factors correlated with it) in explaining the total variation within the data set. In the ordinations for this study, Axis 1 had an eigenvalue of 0.522, indicating that this axis accounted for 52.2% of the of variation in the data and provided good separation of species (Jongman et al. 1995). Axis 2 had an eigenvalue of 0.349, thereby explaining an additional 34.9% of the dataset's variation. With this, Axis 1 and 2 together accounted for 87.1% of the total variation in the dataset. Axis 3 had an eigenvalue of 0.269, therefore explaining relatively little of the total variation in the dataset. Ordination graphs using Axis 3 are therefore not provided in the main body of text, but are given in Appendix J.

Stands at each of the four study sites clustered to a decent degree, as represented by the closed geometric figures representing sites, indicating that there is a definite relationship between marsh developmental stage and the composition of the plant assemblages (Figure 14). Plots from the STBL site are segregated from those of the DIM, INT, and IMM sites to a certain degree, indicating the uniqueness in species composition of many of the plots at the STBL site from those of the other three sites. On the other hand, plot groups representing the DIM, INT, and IMM sites exhibited a certain degree of overlap, which indicates their greater similarity in species composition. The site groups tended to lie in somewhat of a pattern of increasing developmental stage along Axis 1: plots at the

STBL sites lie on the right side of Axis 1, and plots from the other three sites lie toward the left side of Axis 1. With this, environmental controls correlated with Axis 1 are responsible for distinguishing the plant assemblages at the STBL site from those at the sites of earlier developmental stage.

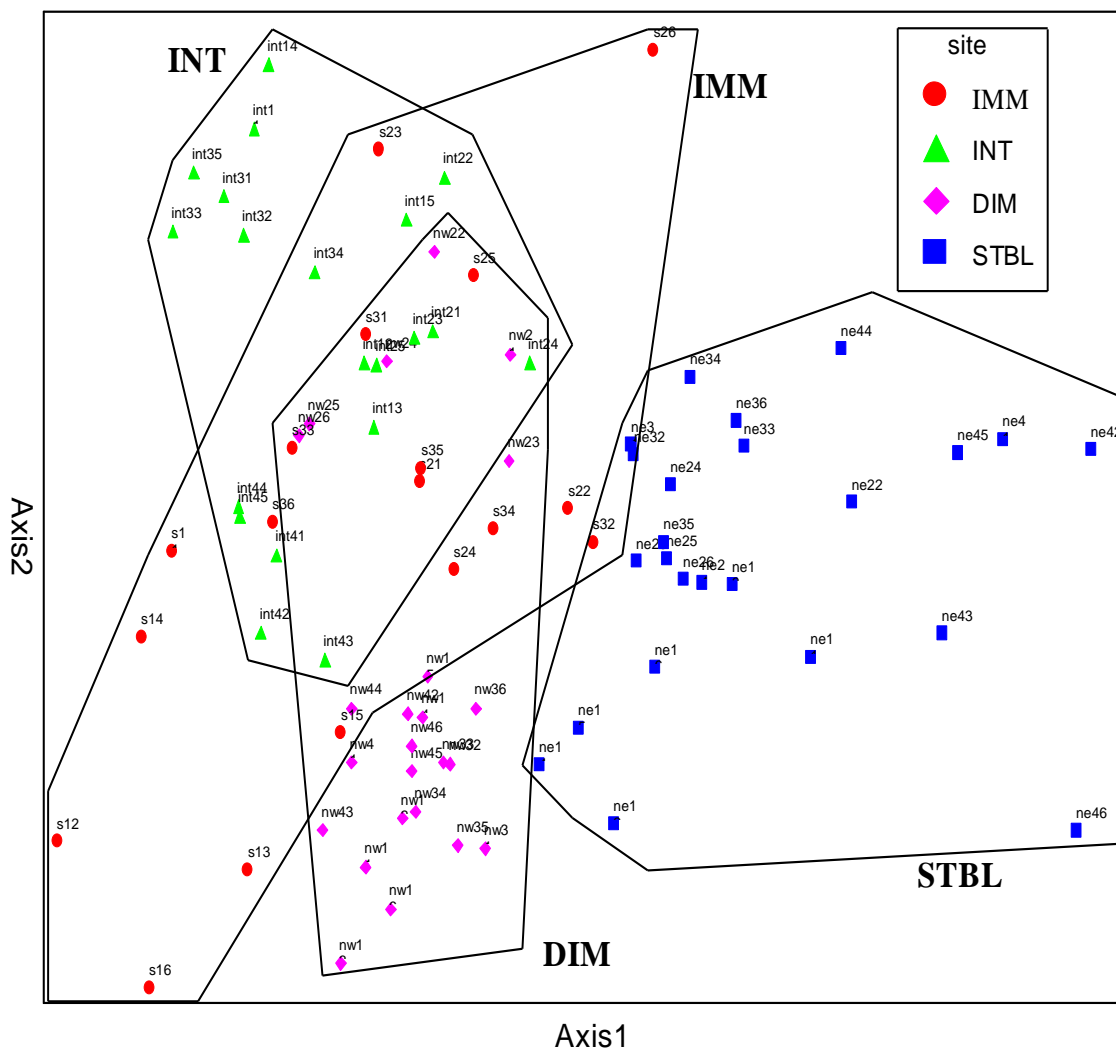


Figure 14. DCA ordination of stands at Russian Island sites (Axis 1 vs. Axis 2).

Stands are shape coded, color coded, and encompassed by a closed geometric figure according to site [IMM, INT, DIM, STBL]. Individual plots are labeled with their location code (e.g. nw) followed by the sampling station number, followed by the quadrat number.

When joint plots (vectors representing measured environmental factors) are superimposed onto the ordination diagram, it is apparent how elevation, soil texture (% sand, % silt, % clay) and organic matter relate to stands at the different sites (Figure 15). The vectors radiate from the centroid of the ordination diagram, and each arrow points in the direction of maximum change for that particular variable across the diagram (Jongman et al. 1995, Kent and Coker 1992). For interpretation

purposes, each vector can be extended backward through the origin, meaning that plots behind the centroid have a lower value for that particular environmental factor. The orientation of the vectors on the diagram supports the results from the descriptive statistics. For example, joint plots representing elevation, sand, clay, and organic matter all point toward the area of the graph heavily populated by plots from the STBL site, which exhibited the highest values for all of these factors. Likewise, these vectors point away from the area of the diagram heavily populated by plots from the IMM site, which exhibited low values for all of these factors.

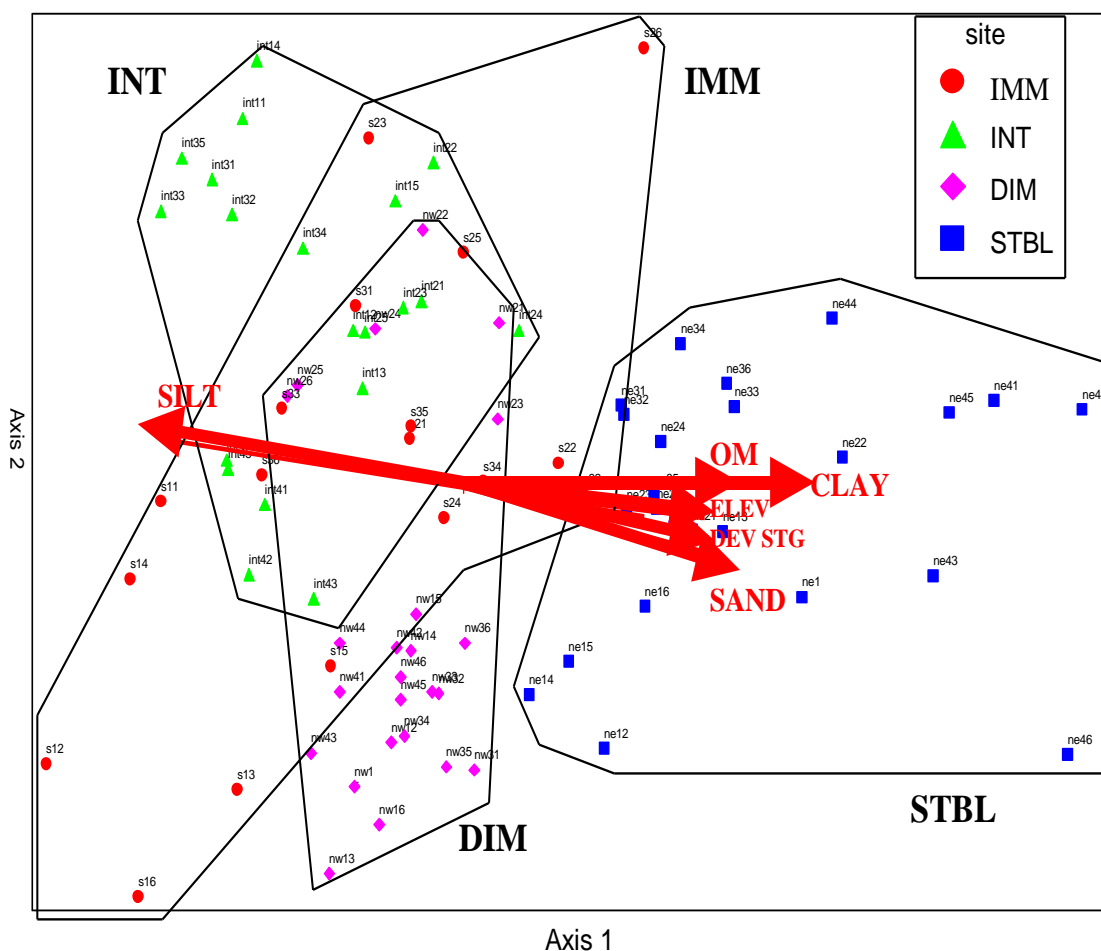


Figure 15. DCA ordination for stands at Russian island sites with joint plots (Axis 1 vs. Axis2).

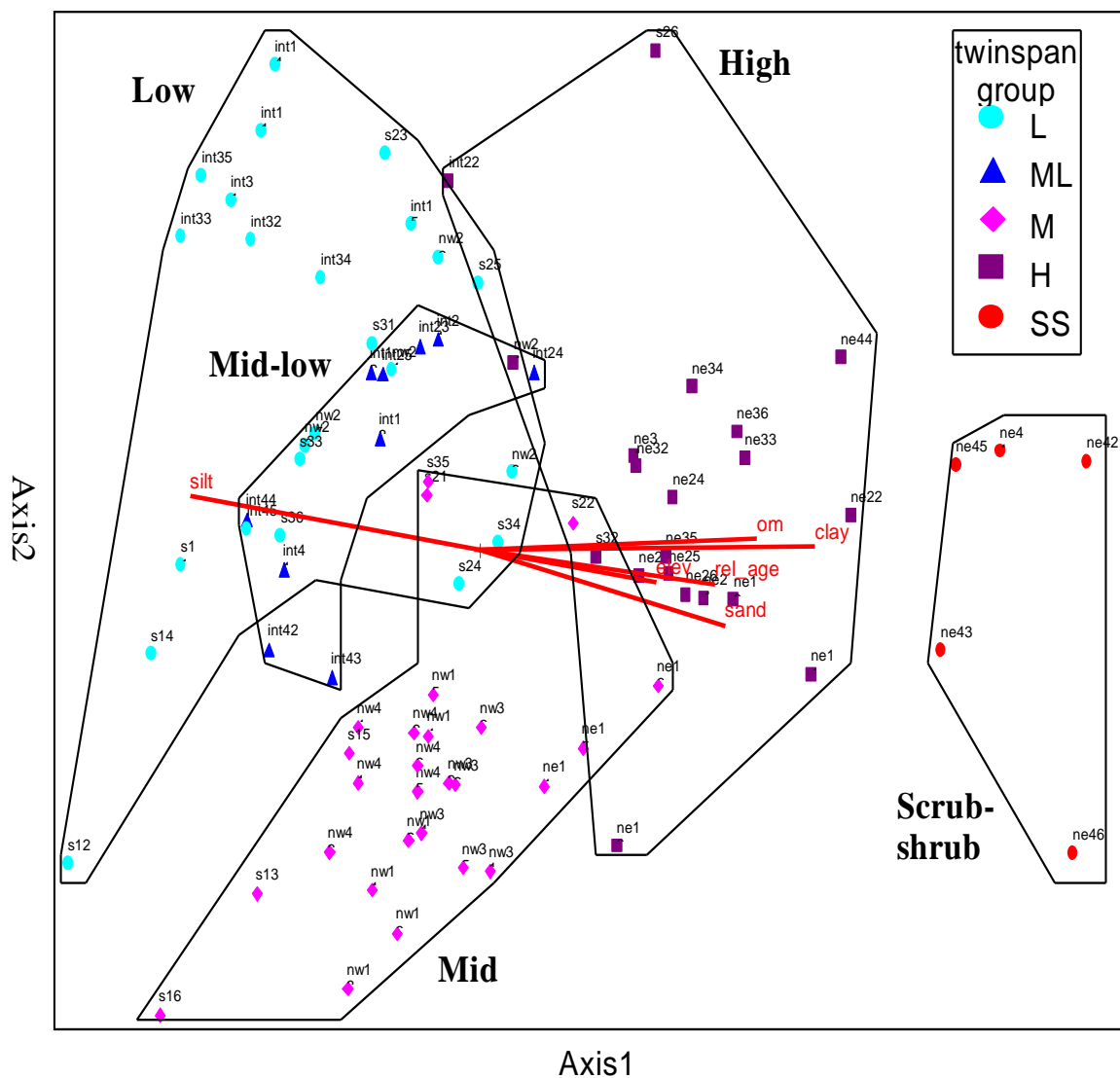
Stands are shape coded, color coded, and encompassed by a closed geometric figure according to site [IMM, INT, DIM, STBL]. Individual plots are labeled with their location code (e.g. nw) followed by the sampling station number, followed by the quadrat number. Joint plots are shown radiating from the centroid in the direction of maximum change with labels denoting the measured environmental factor they represent (silt, sand, clay, organic matter [om], elevation [elev], and developmental stage [dev stg]).

Those vectors that correlate well with a given axis probably serve as one or more of the environmental controls contributing to the importance of that axis in explaining community variation (Jongmen et al. 1995, Kent and Coker 1992). In this study, the vectors representing elevation, soil texture (% sand, % silt, % clay), organic matter, and developmental stage were all highly correlated with Axis 1 (with silt content being negatively correlated with the other factors), meaning that differences in these factors are most likely explaining much of the variation in the surveyed plant assemblages on Russian Island. The importance of developmental stage in influencing the plant assemblages was already suggested by simply the arrangement of site groups on the ordination. Therefore, the idea that the aforementioned factors have a heavy influence on plant assemblage variation is not surprising given their correlation with site, as seen in the descriptive statistics results (e.g., elevation, sand content, clay content, and organic matter content were all highest at the STBL site). Vectors representing soil pore water salinity did not appear on the diagram because there was no apparent trend with the axes, which is to be expected given the lack trends found with the environmental descriptive statistics.

However, the heavy influence of the measured factors is only apparent with regard to plant assemblage variation between the STBL site and the other three sites, since they separated well along Axis 1. As seen in Figure 14, the three sites of earlier developmental stage exhibit a high degree of overlap and weak separation along Axis 1. This makes sense in the context of the descriptive statistics results, where the STBL site was greatly different from the other three sites with regard to the measured environmental factors, but although the DIM, INT, and IMM sites did differ from each other in many respects, there were no consistent difference across all factors.

When TWINSpan groups (L, ML, M, H, SS) were applied to plots on the ordination, more specific clustering occurred than with site groupings, resulting in five fairly distinct groups of stands (Figure 16). This clustering pattern was quite similar to the one created by grouping stands by sites (Figure 14): good separation along Axis 1, illustrating the strong relationship between species composition and developmental stage of site. However, the greater segregation of plots into TWINSpan groups reveals that species associations are not only organized by developmental stage, but also by within-site micro-topographic differences and the environmental factors correlated with them. In this way, the TWINSpan groups reflect floristic variation on both an among-site scale and on a within-site scale. The overlay of measured environmental factors represented by joint plots helps to elucidate this point to some degree. For example, TWINSpan segregated all of the plots in the *Salix* stand (STBL4 sampling station) at the STBL site into a group, which I called “Scrub-shrub”. These plots were characterized by a starkly different species composition from plots of the other

sampling stations at the STBL site, and they also exhibited higher elevation and soil organic matter content, as illustrated by the joint plot overlays and descriptive statistics results. When plots are grouped only by site, on the other hand, clear illustration of the uniqueness of plots from the STBL4 sampling station is lost.



**Figure 16.** DCA ordination of stands at Russian Island sites with TWINSpan classification and joint plots (Axis 1 vs. Axis 2).

Stands are shape coded, color coded, and encompassed by a closed geometric figure according to TWINSpan group [L=low, ML=mid-low, M=mid, H=high, SS=scrub-shrub]. Individual plots are labeled with their location code (e.g. nw) followed by the sampling station number, followed by the quadrat number. Joint plots are shown radiating from the centroid in the direction of maximum change with labels denoting the measured environmental factor they represent (silt, sand, clay, organic matter [om], elevation [elev], and developmental stage [dev stg]).

The greater separation of plots by TWINSPAN groups and their ability to illustrate within-site variation were especially evident with plots of the DIM, INT, and IMM sites. Whereas site groupings of plots exhibited a high degree of overlap, TWINSPAN groupings of plots produced much better separation, especially along Axis 2. For example, even though plots in the Mid-low TWINSPAN group are spread-out across DIM, INT, and IMM sites, they represent relatively low elevation, silty conditions, and are therefore clustered tightly together. Projection of the TWINSPAN groups onto the ordination results in a more ecologically-accurate grouping of plots: plots occurring in the same TWINSPAN group are likely to be found in areas characterized by similar environmental conditions. This reiterates the notion that TWINSPAN groups reflect both among-site and within-site variability in the plant community.

The slight spread of TWINSPAN groups along Axis 2 indicates that environmental controls correlated with this axis are also influencing variation in the plant assemblages, especially at sites of earlier developmental stage. Since none of the factors I measured correlated with Axis 2, factors not addressed in this study must be driving much of the within-site variation in plant assemblages at the sites of earlier developmental stage. This is unlike the within-site variation at the STBL site, where, as discussed above, measured environmental factor differences were found between plots in the Scrub-shrub TWINSPAN group and the rest of the plots at the STBL site, represented by their good separation along Axis 1.

An ordination of species is given in Figure 17. As mentioned, distances among species points are an approximation of their similarity in terms of distribution within the plots (thus, species occurring with exactly the same abundances in the same quadrats would occupy the same point on the diagram). Species that occur close together on the ordination tended to be found in similar environments on Russian Island, and species that occur further away from each other on the graph were found in different environments. For example, *Eleocharis palustris* (ELPA), in the upper-left of the diagram, was found only in the low marsh and in high marsh depressions, areas characterized by lower elevations and silty soils, whereas *Salix sitchensis* (SASI), in the lower-right of the diagram, was found only at the highest elevation in soils of lower silt content. Ubiquitous species that occur in many environments on Russian Island, such as *Carex lyngbyei*, *Equisetum fluviatile*, and *Myosotis laxa*, congregate near the center of the diagram. Two of the most prominent invasive species on Russian Island, *Lythrum salicaria* and *Phalaris arundinacea* also occur here, reflecting their wide tolerance ranges.

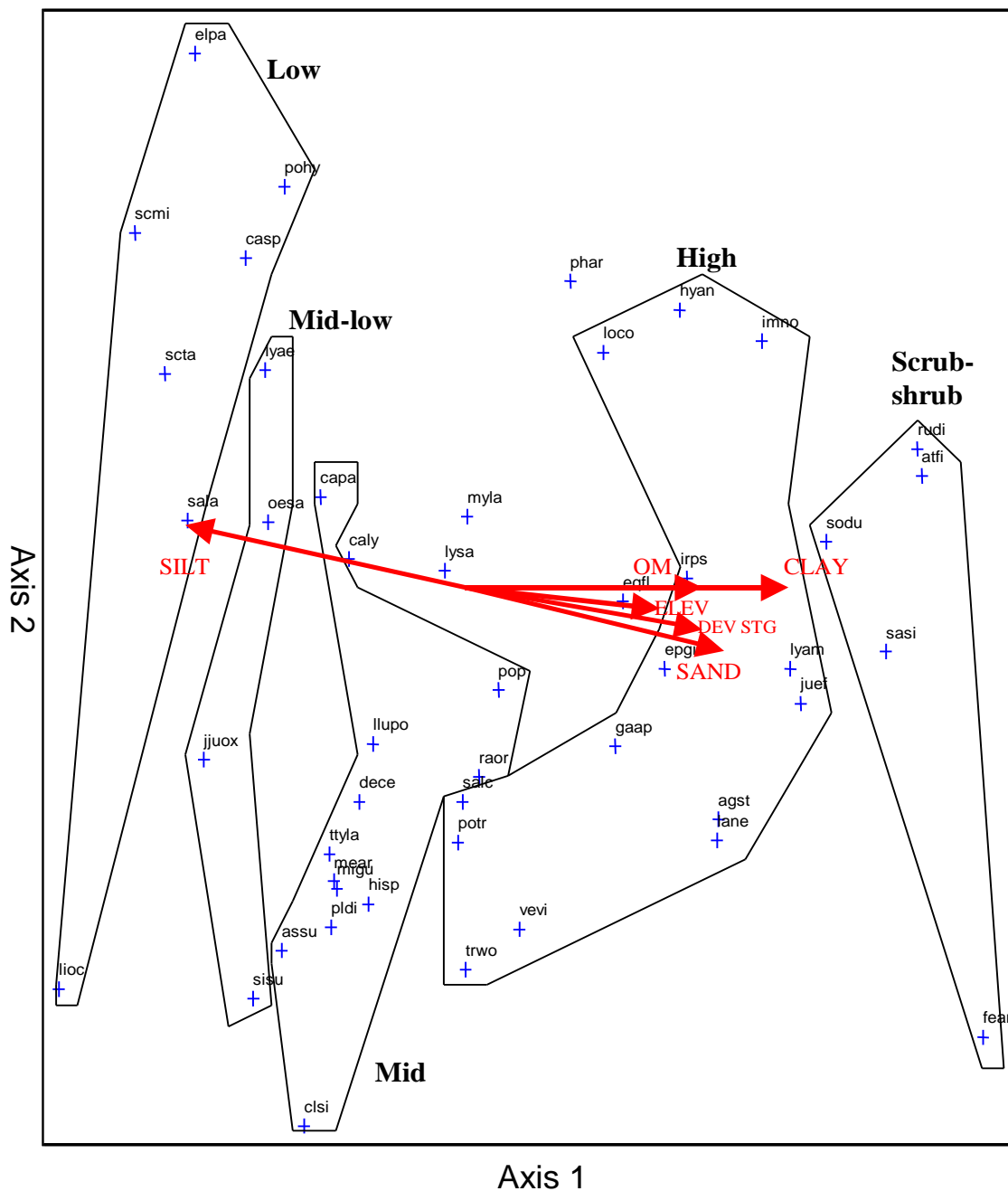


Figure 17. DCA ordination diagram of Species for Axis 1 vs. Axis 2.

Species locations on the ordination diagram are identified by the first two letters of genus and the first two letters (or unique letters if the first two are the same for two species) of the specific epithet (see Table 2 for codes). Species belonging to particular TWINSpan groups [low, mid-low, mid, high, and scrub-shrub] are encompassed with a geometric figure labeled for the particular group. Those species not encompassed by a particular geometric figure are ubiquitous, and do not occur in any one TWINSpan group in particular. Joint plots are also shown.



Like in the previous ordinations, Axis 1 (and the environmental factors correlated with it, such as elevation and soil texture) explains most of the variation in species distribution across the quadrats. This makes sense when inspecting the distribution of species on the diagram in combination with considering their tolerance ranges or habitat preferences (see Appendix H for a description of the general Pacific Northwest habitat for each species). Species on the left end of Axis 1, such as *Callitriche* sp. and *Polygonum hydropiperoides* are tolerant of extremely high levels of inundation and soil saturation, while species on the right end of Axis 1, such as *Festuca arundinacea* and *Salix sitchensis* tolerate lower levels of inundation and soil saturation (Pojar and MacKinnon 1994, Guard 1995). This notion is further illustrated by enclosing species in geometric figures representing their respective TWINSPAN groups: they exhibit a clear arrangement of decreasing elevation from left to right in the ordination. The joint plots help to reinforce this pattern. For example, the elevation joint plot points toward the Scrub-shrub group, comprising species found at the highest elevations and, likewise, the least tolerant of inundation (such as *Salix sitchensis*), while it points away from the Low group, species found at the lowest elevations, comprising species tolerant of extreme inundation (such as *Eleocharis palustris*). The soil texture joint plots, similarly, reinforce species habitat tendencies. For example, the joint plot representing silt points almost directly at *Sagittaria latifolia*, a species observed mostly in high marsh depressions, which were characterized by high silt content. Likewise, this species is known to be found in silty, mucky soils characterized by high levels of inundation (Guard 1995). With this, the distribution of species on the ordination, their relationship to superimposed joint plots indicating measured environmental factor gradients, and previous knowledge of species tolerance ranges tend to bolster each other. Significant spread in the distribution of species is also observed along Axis 2, which corroborates the notion that environmental factors not measured in this study are influencing the plant assemblages on Russian Island.

## 4.0 DISCUSSION

The objective of my research was to explain as much of the variability in the Russian Island plant community as possible. This was accomplished in a field study that explored large-scale and small-scale variation in the island's plant assemblages and investigated environmental factors that may be influencing that variation. Large-scale community variation was addressed by assessing differences in the plant assemblages and environmental factors at four sites on the island representing different marsh developmental stages (STBL, DIM, INT, IMM). Likewise, small-scale variation at the tidal channel level was addressed by investigating plant assemblage and environmental factor differences associated with micro-topographic variation perpendicular to the main access channel at each site. In addition, landscape-scale differences were addressed in an island-wide plant community analysis using GIS. To summarize, variation in the Russian Island plant community assessed in the field study was found on both scales, and appeared to be driven by a combination of elevation, soil texture, soil organic matter content, and factors not investigated in this study. The landscape-scale GIS analysis, a fusion of remote sensing and field knowledge, produced a depiction of the Russian Island plant community that more completely addressed island-wide differences than did the field study alone. This product allowed for the comparison of current to historic vegetation types, resulting in the development of a model for plant community evolution on Russian Island.

### 4.1 Environmental factors

Elevation, soil texture, and soil organic matter were found to be most influential in driving among- and within-site variability in the plant assemblages on Russian Island. As previously discussed, these factors were found to be important to plant community structure in other tidal marsh studies (Jefferson 1975, Eilers 1975, Burg et al. 1976, Disraeli and Fonda 1978, Ewing 1986, Ewing 1983). With this, my predictions of the influence these factors on the Russian Island plant were well founded and confirmed.

However, when reviewing these results in the historical and fluvial geomorphic context, it appears that the among-site differences in these factors are greatly a product of developmental stage. For example, elevation was found to be highest at the STBL site and lowest at the IMM site (Figure 5), which makes sense given that the STBL site represents long-term marsh development (and has accreted sediment for the longest period of time), and the IMM site represents short-term marsh development (and has accreted sediment for the shortest period of time). The exposure of the DIM site is illustrated by its comparable elevation to a site of earlier developmental stage, the INT site. Even though the DIM site has existed for a longer period of time, greater disturbance forces on this

side of the island nearest the primary estuary channel has kept the elevation relatively low. The INT site is younger, but is protected from erosional forces, so it has been slowly accreting sediment and growing in elevation. In terms of soil texture, sand and clay content were highest at the STBL site (latest developmental stage), while the sites of earliest developmental stage have the highest silt content (Figure 6). This trend also makes sense in a historical context. Prior to flow alteration when the STBL site was formed, the Columbia River was characterized by a wider range in its flow rates, with extremely large flood events and periods of low discharge (Sherwood et al. 1990). Flood events carried and deposited sediments of larger diameters, sand, while low flows could only suspend sediments of small diameter, fine silt and clay (Brady and Weil 1999, Jay et al. 1990). This historic variety in sediment deposition may be the cause of soils characterized by a more even distribution of sand, silt, and clay in areas of later developmental stage, such as the STBL site (Figure 7). In contrast, sites of earlier developmental stage have been developing under the altered flow regime, characterized by consistent, slow velocity flows that suspend only medium sized, similar diameter sediment particles (Jay et al. 1990). With this, soils at sites of earlier developmental stage (INT and IMM) exhibited a higher silt content and a more lopsided distribution of silt relative to sand and clay (Figures 6 and 7). Also, in terms of spatial heterogeneity in fluvial geomorphic processes affecting soil texture, the sand content is lowest at the INT site, which is most likely due to the sheet-flow phenomenon (discussed in the Introduction). Organic matter was highest at the site of latest developmental stage (STBL), especially at the most inland sampling station. The higher elevation at this site, and resulting lower frequency of tidal inundation and water flow to transport detritus, has most likely allowed for the greater accumulation of organic matter relative to other sites. The especially high value at the most inland sampling station appears to be related to the presence of a Scrub-shrub component: the willow stand was characterized by a large amount of downed debris that appeared to be capturing detritus and creating a substantial duff layer (pers. obs.).

Within-site differences in the aforementioned factors were also observed. Elevation differences between sampling stations represented the micro-topographic variation perpendicular to the tidal channel encompassing areas of low marsh (LM), high marsh (HM), and high marsh depression (HMD) (Figure 5). Soil texture also varied among sampling stations, with the most notable differences being high silt in the LM and HMD (Figure 6). There was also a trend of increasing organic matter with increasing distance from the access channel (Figure 8), which is not surprising given that detritus near the channel is most likely to be transported off-site by water flow.

In summary, there was a general increase in elevation, evenness in sand, silt, and clay distribution in soil, and soil organic matter content with developmental stage, a relationship that appears to be directly tied to the spatial heterogeneity in fluvial geomorphic processes that have

shaped Russian Island over time. Within-site differences were also observed, with micro-topographic variation perpendicular to the access channel (e.g. lower elevations in LM and HMD), soil texture differences (higher silt in HMD), and higher soil organic matter at inland sampling stations.

Although elevation and soil property differences associated with developmental stage and micro-topography appeared to be the main drivers of plant assemblages on Russian Island, other factors must also be influential. This was apparent with the lack of separation of the first three TWINSPAN groups (those plots at sites of earlier developmental stage) along Axis 1, the axis correlated with all of the measured environmental factors, and their better separation along Axis 2. The distribution of species also exhibits significant spread along Axis 2. Environmental and biological factors found to influence marsh plant community variation in other studies that may be causing variation in the plant assemblages on Russian Island include, soil aeration/soil redox potential (Armstrong 1985, Ewing 1983, Mendelsohn 1982), nutrient levels (Levine et al. 1998, van Wijnen and Bakker 1999), soil temperature (Ewing 1983), competition (Grime 1979), and herbivory (Crandell 2001, Dormann 2000). Localized effects of grazing by Canada geese were observed on field visits to Russian Island. Patches (generally 15-30 m) of high marsh adjacent to tidal channels were characterized by grazed *Carex lyngbyei* shoots, abundant goose feces in the early part of the growing season, and the unusual dominance of *Lotus corniculatus* and *Myosotis laxa* in assemblages otherwise dominated by *Carex lyngbyei* (pers. obs.). Other animals, such as beaver and nutria, have had a documented impact on other wetlands in the estuary (Dunn et al. 1984). Likewise, these mammals may be influencing the plant assemblages on the Russian Island through hydrological modification, local disturbance, and the transport of plant materials.

While salinity is often the most influential factor in other estuarine marshes in Oregon (Jefferson 1975), it was not found to be an important factor driving variation in the plant assemblages surveyed on Russian Island, given the lack of a trend among sites or within sites. However, contrary to what would be suggested from estimates in other studies (Macdonald 1984, Fox 1984), slight salinity levels (up to 2.60 ppt) were found to be present in soil pore water on Russian Island, and may be influencing the plant community as a whole. The trend across sites of an increase from May to June, but a decrease thereafter made sense in the context of the Columbia River's flow rates. The freshet for 2003 began the second week in June, which was after the sampling trip for that month (BPA 2003). This freshet bombarded the estuary with freshwater, thereby diluting its salinity and decreasing the soil pore salinity in the subsequent two months of sampling.

## 4.2 Plant assemblages

Because of the unique, high flow of the Columbia River, the plant assemblages of Russian Island and the other remaining freshwater tidal marshes in the estuary exhibit high species diversity that is virtually unmatched elsewhere in the Pacific Northwest (Table 2). Such results are not surprising because tidal marshes of higher salinity are known to be less diverse than their freshwater counterparts (Mitsch and Gosselink 2000).

**Table 2. Diversity comparison of plant communities studied in various Pacific Northwest estuaries.**

Study	Gamma diversity	Location
Elliot 2004	47	Columbia River
Macdonald 1984	48	Columbia River
Burg et al. 1980	24	Nisqually, WA
Disraeli and Fonda 1978	12	Bellingham Bay, WA
Ewing 1983	30	Skagit, WA
Hutchinson 1988b	19	Fraser, B.C.
Liverman 1981	37	Tillamook, OR

Within the Russian Island plant community, site differences in species richness and diversity were also observed, with a tendency for both measures to increase with developmental stage, until a scrub-shrub component is introduced. To illustrate this, the DIM site had the highest species richness and diversity, exceeding that of the site of latest developmental stage, STBL (Figures 10 and 12). This lower diversity at the STBL site is most likely due to the strong presence of willows, excluding the shade-intolerant members of the diverse high marsh matrix (such as *Carex lyngbyei*). Also potentially adding to the lower diversity here is the greater presence of invasive species. While not forming large stands, small patches of *Phalaris arundinacea* and *Lythrum salicaria* are still established at the STBL site. In addition, invasive species usually found in drier habitats, such as *Rubus discolor* were also observed. This relatively high invasive species presence at the STBL site can potentially be explained by disturbance inflicted by beavers and nutria, which were observed to have a strong presence at the site (e.g., large beaver lodge, beaver dam, trail network). The diversity at the IMM site was particularly low, explained by its early developmental stage, low elevation, and strong presence of invasive species. *Phalaris arundinacea* and *Lythrum salicaria* form extensive monotypic stands at this site.

As mentioned, the among- and within-site differences in the discussed environmental factors have influenced the plant community on Russian Island, and these two scales of variation are reflected in the five vegetation groups identified in this study: 1) *Low*, 2) *Mid-low*, 3) *Mid*, 4) *High*, and 5) *Scrub-shrub*. DCA ordination was used to visualize difference between these groups and how they relate to measured environmental factor gradients, and the following paragraphs comprise a verbal description of the groups.

The *Low* group was characterized by species tolerant to extreme inundation and prolonged standing water, such as *Eleocharis palustris*, *Scirpus tabernaemontani*, *Callitriche* sp., and *Lilaeopsis occidentalis*. Stands in this group were located only at the site of earliest developmental stage (IMM) or in the low elevations (in the low marsh and in high marsh depressions) at the INT and DIM sites. None of the stands in this group were at the site of latest developmental stage, STBL. Soils in this group tended to have high silt content and low sand content, and were, thus, often quite mucky. Given that plots of this group occurred at the lowest elevations, this group was also characterized by the highest levels of tidal inundation.

The *Mid-low* group was characterized by species tolerant of high inundation and fluctuating water levels, such as *Carex lyngbyei*, *Oenanthe sarmentosa*, *Sagittaria latifolia*, and *Polygonum hydropiperoides*. Plots in this group were located only at the two sites of earliest developmental stage (INT and IMM), in the low marsh and in the high marsh, but not in the high marsh depression. Soils in this group tended to have slightly higher sand content and slightly lower silt content than soils of the *Low* group. This group was also characterized by high levels of inundation, but not to as great of an extent as the *Low* group.

The *Mid* group was characterized by species quite tolerant of inundation and fluctuating water levels, such as *Carex lyngbyei*, *Deschampsia caespitosa*, *Mentha arvensis*, and *Mimulus guttatus*. Stands in this group were located at all sites except INT, but were mostly at the DIM site in the high marsh. Soils in this group tend to exhibit a slightly lower silt content and a slightly higher sand content than the *Mid-low* group. This group also is characterized by relatively high levels of inundation, since its stands occur only at slightly higher elevations than the *Mid-low* group. This group and the high group comprise the majority of vegetation types surveyed on Russian Island.

The *High* group was characterized by species tolerant of extremely saturated soils, such as *Lysichiton americanus*, *Iris pseudacorus*, *Hypericum anagalloides*, and *Impatiens noli-tangere*. Most of the stands in this group were located at the STBL site. Soils in this group, along with the *Scrub-shrub* group (also at STBL site) had the highest sand and clay content in the study. Elevations in this group were high, second only to the *Scrub-shrub* group. Species diversity was not as high here as in the *Mid* group, probably due, in part, to the partial exclusion of the shade-intolerant high marsh matrix

by the presence of willows. However, diversity was not as low as in the Scrub-shrub group that was completely dominated by willows.

The *Scrub-shrub* group was dominated by *Salix sitchensis*, with *Festuca arundinacea*, *Rubus discolor*, and *Athyrium filix-femina* also being common. These are species not adapted to as high of a level of inundation as others on the island and are often found in transitional areas between wetlands and uplands (Pojar and MacKinnon 1994, Guard 1995). The plots of this group were located only at the site of latest developmental stage at the highest elevation (STBL4), and were completely encompassed by a large stand of *Salix sitchensis*. Also, the plots in this group were the only ones in the study located above MHHW (2.47 m). Soils of this group were similar to those in the *High* group, except with higher organic matter content. As previously discussed, this is probably due to the tendency for detritus to be captured in the willow stand, as was witnessed during field visits. As mentioned, species diversity in this group was exceptionally low.

The low marsh general vegetation type described in the Introduction is composed of a combination of the *Low* and *Mid-low* groups. The high marsh general vegetation type is a combination of the *Mid-low*, *Mid*, and *High* groups.

Although species were mentioned as characterizing certain TWINSPAN groups, it does not mean that their occurrence was isolated to that group. Many species were found in a variety of habitats, while some were, in fact, restricted to a vegetation type. Species found in many groups, such as *Carex lyngbyei* and *Lythrum salicaria* are tolerant of a wide range of environmental conditions, whereas those found in only one or two vegetation types, such as *Sagittaria latifolia* and *Epipactus gigantean* tend to be more sensitive. The species list provided in Appendix H includes the general vegetation types on Russian Island in which each species is found, while Appendix I includes the frequency with which each of the species occurs in the various TWINSPAN groups.

This in-depth discussion of vegetation types found at the four study sites on Russian Island expands on the lower Columbia River estuary wetland characterizations by Thomas (1984) and Macdonald (1984). Although vegetation types identified by these two researchers captures the majority of the Russian Island plant community (low brackish marsh, low and high freshwater tidal marsh, and scrub-shrub), the coarse scale necessitated by the large scope of their estuary-wide projects precluded refinement of these vegetation types to capture local variation. The comparatively smaller scope of my study allowed for this level of focus. The five assemblage types identified and described in detail in this study reflect both large-scale (island-wide) and small-scale (tidal channel level) variation in plant assemblages on Russian Island. In addition, although Macdonald's (1984) research did address environmental factor influences on overall plant productivity, no study, until this one, has

related direct measurements of environmental variables to the compositional variation in plant assemblages of freshwater tidal marshes in the lower Columbia River estuary.

### 4.3 Summary of field study

To summarize the field study component of my research, variation in the plant community on Russian Island was found on both large and small scales: among-site and within-site. Among-site differences appeared to be driven by elevation, soil texture, and organic matter: factors directly related to spatial heterogeneity in the fluvial geomorphic processes that have shaped the island. The most striking among-site plant assemblage differences were evident only between the site of latest developmental stage (STBL) and the other three sites, as was evident by the high degree of overlap exhibited by DIM, INT, and IMM sites in the ordination. As was shown by the better separation achieved with TWINSPAN groups, plant assemblages are also influenced by within-site differences. While small-scale variation at the site of latest developmental stage appeared to be driven by the same factors driving among-site differences, variation in the plant assemblages at the sites of earlier developmental stage appeared to be influenced more by factors not addressed in this study.

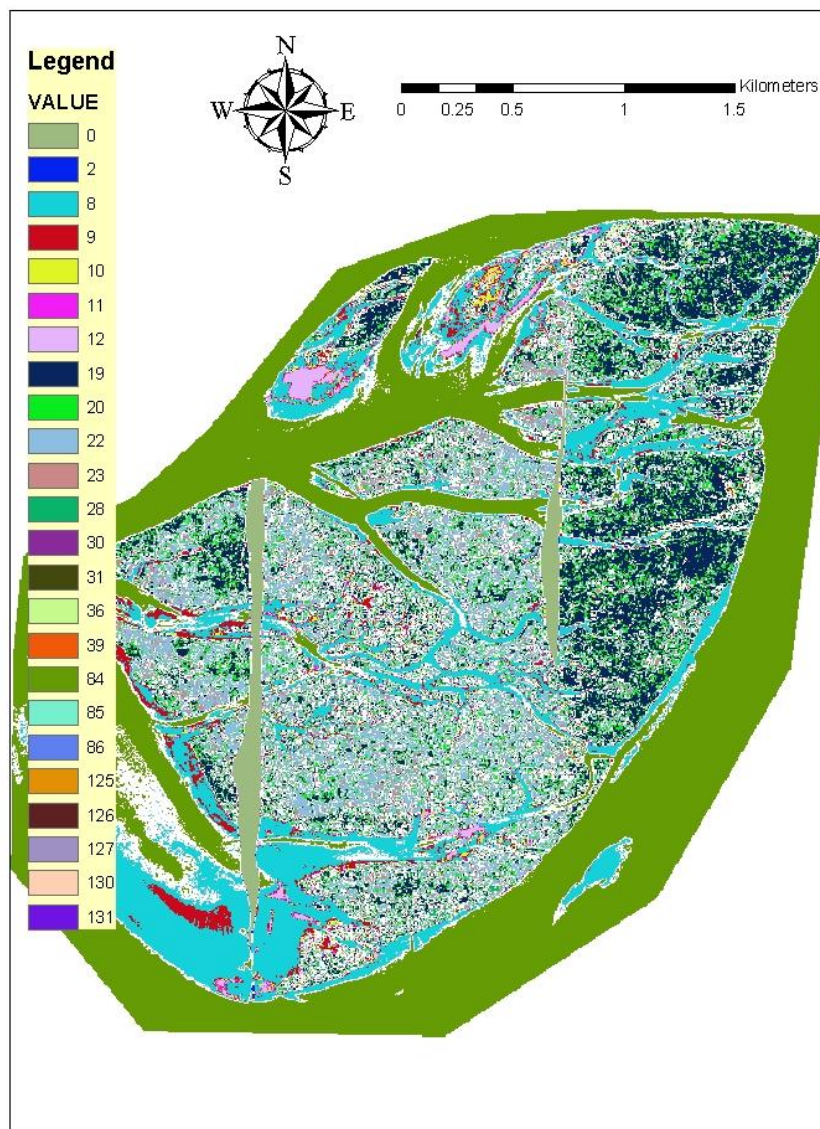
My research has filled part of the gap in the understanding of relationships between the plant assemblages and their controlling environmental factors in the freshwater tidal marshes of the lower Columbia River estuary. Restoration and conservation planners need to consider variability in the discussed factors on both large and small scales, as well as the impact of invasive species and how to manage them, to achieve the goal of rehabilitating these habitats in the estuary. However, as shown by the incomplete explanation provided by the environmental factors measured in this study, much opportunity exists for further studies of plant community ecology in this system.

### 4.4 GIS Analyses

With the development and refinement of GIS and remote sensing technologies, there has been growing popularity in recent years to use remote sensing for mapping and characterizing large areas of habitat, a trend also occurring in the lower Columbia River estuary (Simenstad 1999). One of the most recent developments in this field is Compact Airborne Spectrographic Imager (CASI) imagery. The images created by CASI are hyperspectral, where the CASI sensor collects reflectance data in 19 spectral bands, and has an extremely high spatial resolution of 1.5 meters (Garano et al. 2003). For comparison, multispectral Landsat imagery, which is often used for habitat classification, represents reflectance data collected in seven spectral bands with a spatial resolution of 30 meters. A CASI



image created in 2001 by supervised classification (ground-truthing at target locations used for spectral references) of Russian Island provided by Earth Design Consultants (Corvallis, OR) is shown in Figure 17. This original classification resulted in 22 habitat classes on Russian Island (Table 8).



**Figure 18. Original CASI image of Russian Island, courtesy of Earth Design Consultants, Corvallis, OR.**

**The original CASI classes are shown in the legend and numerical classes are defined in Table 8.**

**Table 3. Original CASI classes and their numeric representative.**

Use Table to define legend on Original CASI image.

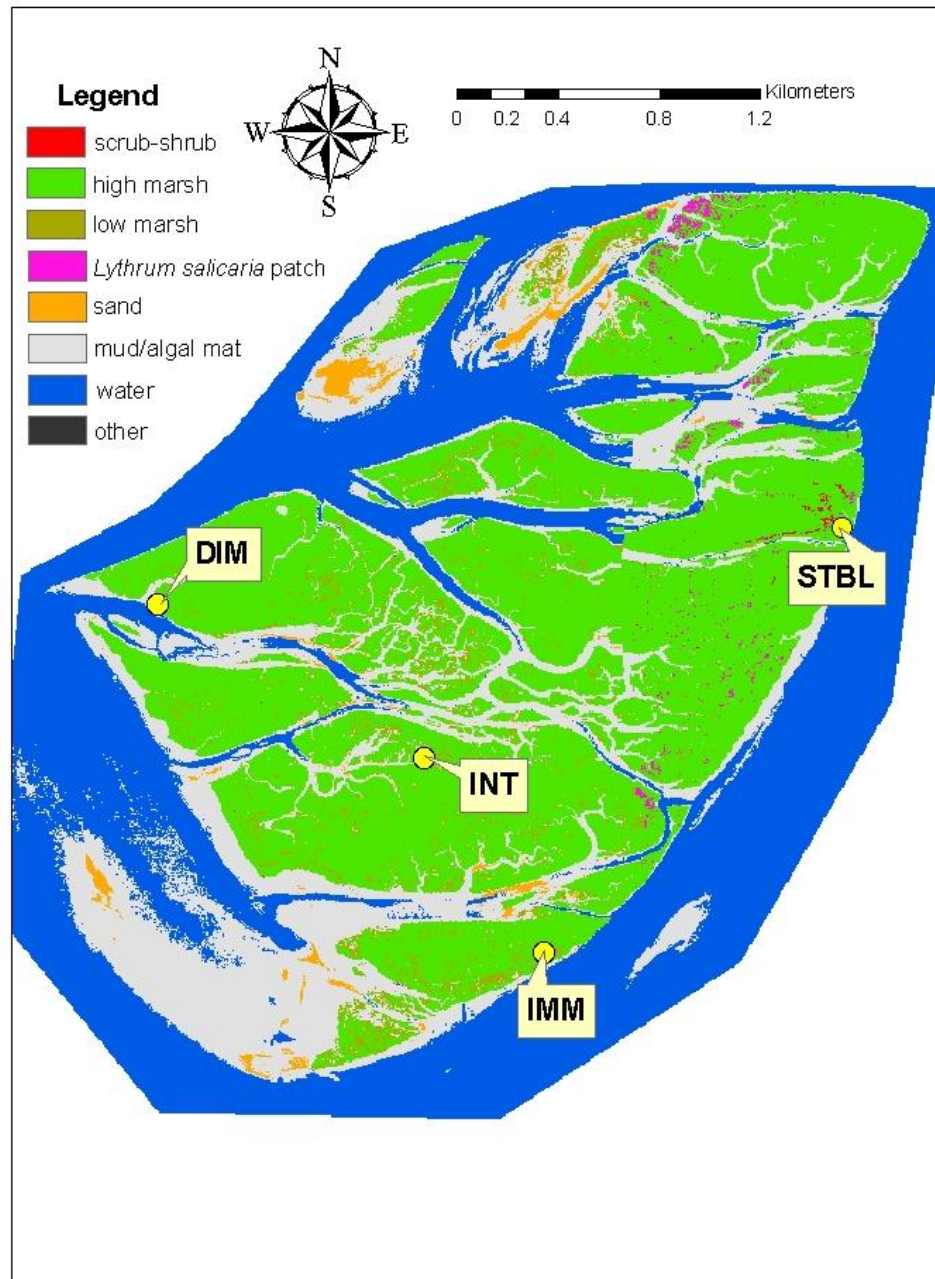
127	Conifer (shrub/scrub)
126	Deciduous (shrub/scrub)
131	Conifer
130	Deciduous
31	Broad-leaved: Polygonum, Scirpus, Sagittaria
22	Sedge (dense)
23	Sedge (sparse)
125	Unspecified (Herbaceous wetland)
19	Unspecified (Wetland Shrub/Scrub)
2	Buildings
39	Broad-Leaved: Medium Purple Loosestrife
36	Broad-Leaved: Dense Purple Loosestrife
10	Mud/Broad_Leaved
11	Mud/Rush
28	Rush (Eleocharis)
30	Rush (Lilaeopsis on Mud)
12	Sand
84	Water
85	Other (Boats, Docks)
86	Other (Targets)
9	mud/ algal mat
20	green algae
8	mud
0	no data

After scrutinizing the CASI image, and comparing its classification to my field observations of the plant community organization, I realized that the classes in the imagery weren't completely reflecting true ecological groupings. Although precise for the most part (some imagery misclassifications were apparent and had to be addressed), I found that many of the CASI classes were not mutually exclusive in the field. For example, "mud/rush" and "rush (eleocharis)", distinct CASI classes, were not actually distinct vegetation assemblages. Keeping my field observations of co-existing plant species and vegetation community structure on Russian Island in mind, the level of resolution with the CASI imagery that revealed itself to me was on the order of high marsh vs. low marsh, along a stark elevation gradient. With this, I collapsed and reclassified some the CASI groups into classes that corroborated my field observations, and these results are shown in Table 9.

**Table 4. Revised CASI classification.**

Original CASI habitat classification	Revised CASI habitat classification
Conifer (shrub/scrub)	scrub-shrub ( <i>Salix</i> )
Deciduous (shrub/scrub)	
Conifer	
Deciduous	
Broad-leaved: Polygonum, Scirpus, Sagittaria	high marsh
Sedge (dense)	
Sedge (sparse)	
Unspecified (Herbaceous wetland)	
Unspecified (Wetland Shrub/Scrub)	
Buildings	
Broad-leaved: Medium Purple Loosestrife	<i>Lythrum salicaria</i> patch
Broad-leaved: Dense Purple Loosestrife	
Mud/Broad-leaved	low marsh
Mud/Rush	
Rush ( <i>Eleocharis</i> )	
Rush ( <i>Lilaeopsis</i> on Mud)	
Sand	sand
Water	water
Other (Boats, Docks)	other
Other (Targets)	
mud/algal mat	mud/algal mat
green algae	
mud	

The CASI image with revised classes is shown in Figure 18. Also, as can be seen in Figure 17, the original CASI image had two swaths of missing data (where the flight lines of the airplane did not overlap). These swaths were filled in the revised image using ArcTools GridEdit (see “GIS methodology” for detailed description) (Figure 18). Russian Island study sites are also shown in their exact location by way of GPS.



**Figure 19. Revised CASI image of Russian Island.**  
**Study sites are labeled and marked with yellow points.**

The accuracy of the CASI imagery was reviewed by comparing its interpretation of the vegetation assemblages at the Russian Island study sites with findings from my field study. As is shown in Appendix K, there are limitations with CASI imagery on extremely small scales (i.e., 30 m

transects characterizing my study sites). However, after being edited based on field knowledge, the picture it painted of the Russian Island plant community on the whole (~7 sq. km) is quite accurate, and addresses island-wide differences more completely than did the field study alone. The image showed the dominance of the high marsh vegetation type and presence of low marsh assemblages (Figure 18). It also detected scrub-shrub assemblages and the presence of invasive species. When this level of accuracy is applied to an area as large as the entire lower Columbia River estuary (which is the extent of the project that produced the Russian Island image), the resulting large-scale characterization is an indispensable resource for researchers and policy makers. And as the accuracy of these imagery technologies continues to improve, the amount of information that can be gleaned by them will increase exponentially.

A major benefit of GIS-based remote sensing technologies is that although they produce images that only represent a snapshot in time, they are georeferenced and can be compared to historic images to help create a model for change in landform or habitat over time, potentially leading to the development of hypotheses of reasons for that change. Using these comparisons to investigate geomorphological change is exemplified by my methodology for choosing research study sites on Russian Island. As previously discussed, the sites were chosen based on a comparison between an 1870 topographic sheet (historical marsh extent) and a 2000 digital ortho-quad (current marsh extent), revealing areas of different marsh development induced by spatial variation in fluvial geomorphological processes (Figure 4). If historic and current datasets are characterized by high resolution and habitat classifications, as are the 1870 t-sheet and a map depicting current Russian Island vegetation types (to be discussed shortly), comparisons of historic to current habitat type can also be made to produce a model for habitat change over time. Marsh habitat classes on the Russian Island component of the 1870 t-sheet are robust, consisting of “emergent wetland” and “intertidal emergent wetland”. These two classes, as well as four others relating to tidal channel habitats, are denoted by differences in hash mark type and frequency, in addition to variations in boundary markings. I digitized habitat classes using methodologies developed by Jennifer Burke, NOAA Fisheries (Burke 2003) (see “GIS methodology” for detailed description). The resulting digitized habitat polygon coverages are shown on the map in Figure 19.

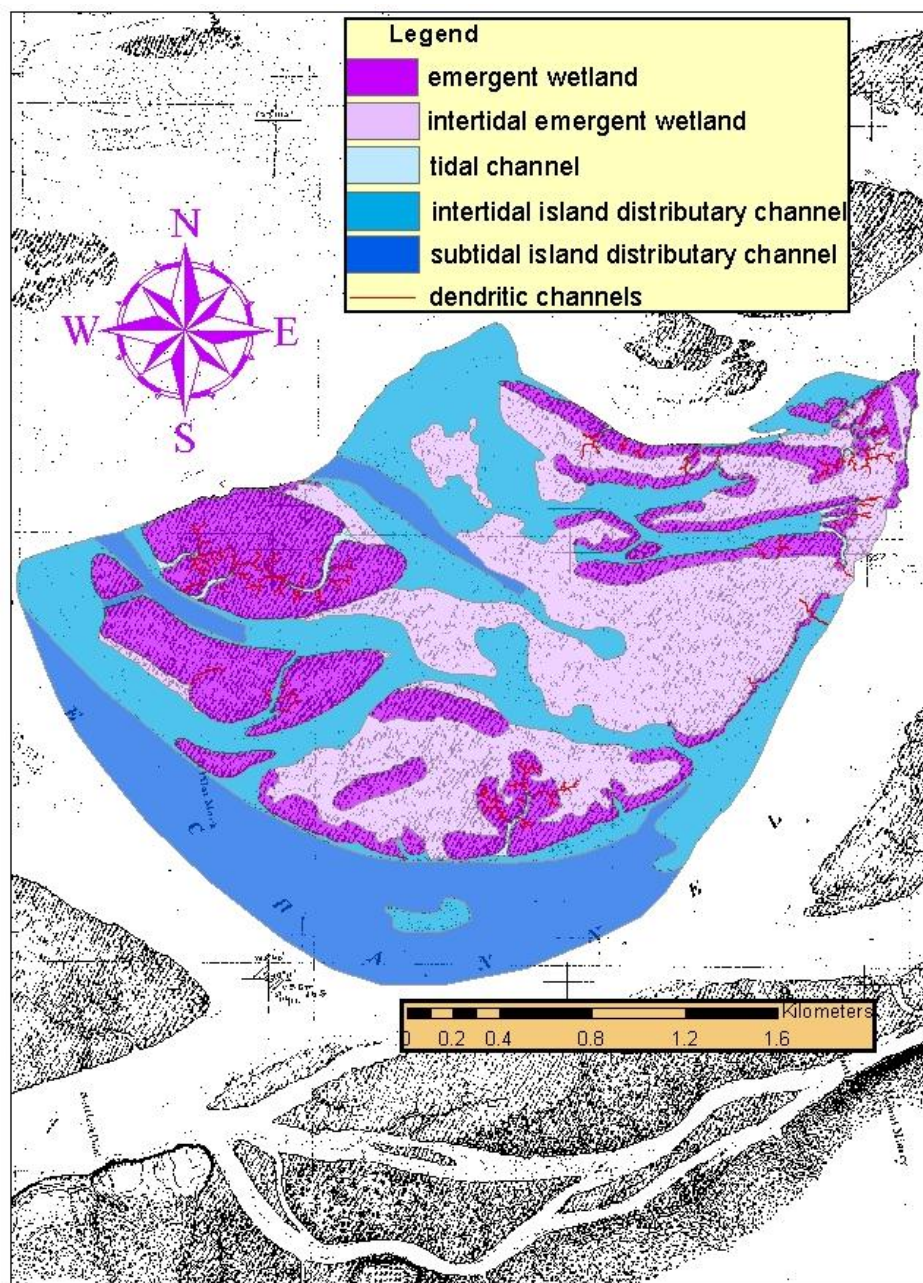
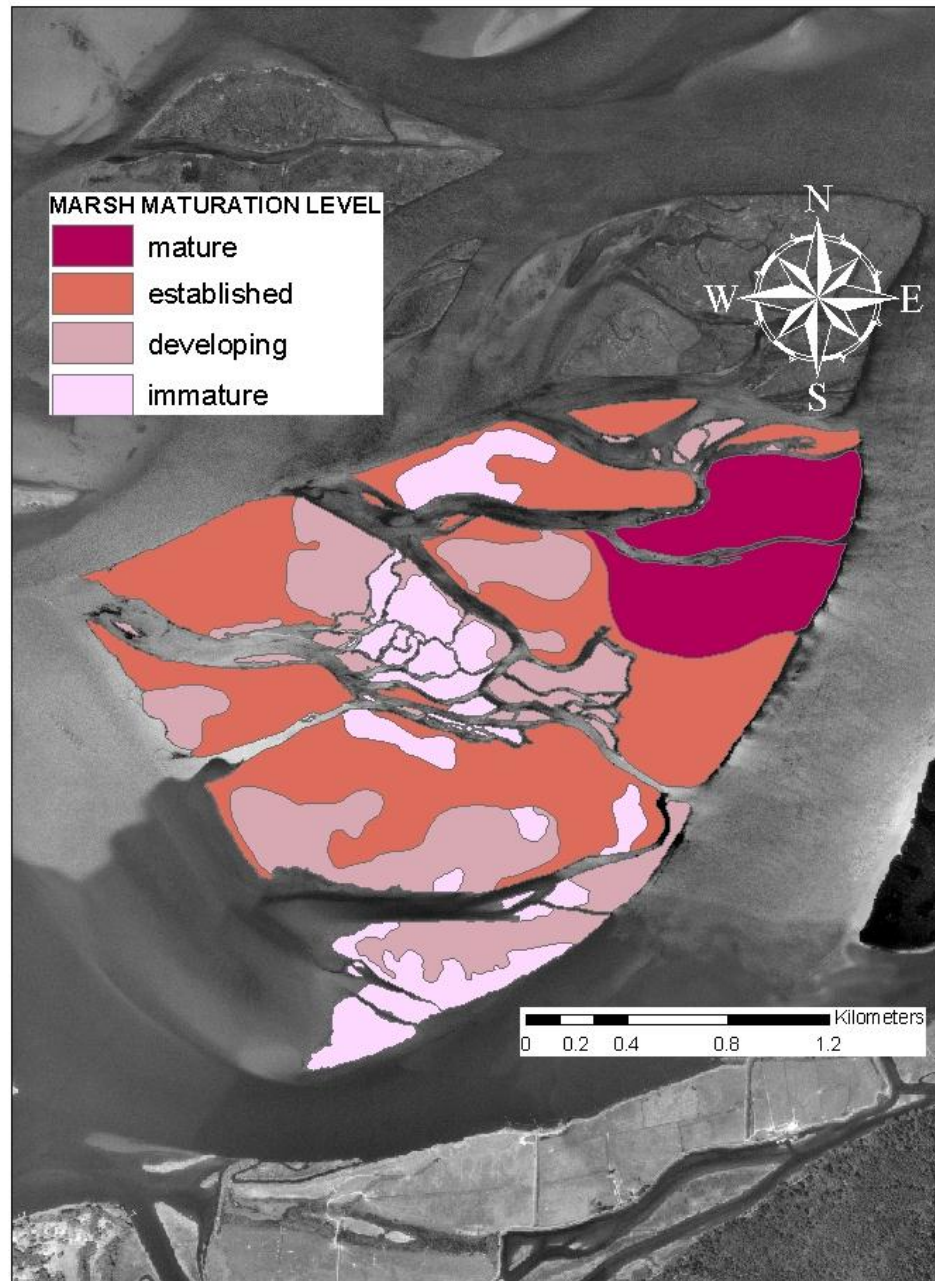


Figure 20. Historic habitat types on Russian Island digitized on an 1870 topographic sheet.

1870 topographic sheet (U.S. Coast and Geodetic Survey; provided by Jennifer Burke, NOAA Fisheries) shown in black and white. Digitized habitat types include; emergent wetland, intertidal emergent wetland, tidal channel, intertidal island distributary channel, subtidal island distributary channel, and dendritic tidal channel.

A map of current Russian Island vegetation types was created in a two-step process. First, the 2000 DOQ, with highly precise landform boundaries, was used to digitize the current Russian Island extent (sub-islands, tidal channels, etc.). Then, the CASI imagery was used in combination with my field-based knowledge of the plant community to classify the digitized polygon coverages in terms of relative marsh maturation level (see “GIS methodology” for detailed description). The resulting map is pictured in Figure 20.



**Figure 21. Current marsh habitat types as a function of relative maturation level on Russian Island.**

Marsh maturation levels are as follows: 1) Immature - included areas with high frequencies of large low marsh patches; 2) Developing - included areas with lower frequencies of smaller low marsh patches; 3) Established- included areas that had low frequencies of small and isolated patches of low marsh; 4) Mature - included areas characterized by scrub-shrub habitat and where low marsh was mostly isolated to channel edges.



In comparing the historic map to the current map, it is apparent that high marsh (represented as “emergent wetland” on the historic map, and represented as “developing”, “established”, and “mature” maturation levels on the current map) area on Russian Island is increasing, indicating a net accretion of sediment, a trend consistent with the model for the estuary as whole (Sherwood et al. 1990). Another attribute characterizing the evolution of Russian Island is the development of a substantial scrub-shrub (*Salix*) component, which had not even appeared on the island by the 1870 survey. This idea in combination with the age stratified study sites illustrating the trend of increasing woody component with developmental stage, suggests a general model of succession occurring on the island. Given the lack of river disturbance that historically played such a huge role in perpetuating habitats of earlier successional stages, movement of the marshes on a trajectory toward scrub-shrub systems seems quite feasible. Such a change has ecosystem-wide implications (such as decreased diversity, as seen in the field study), and definitely deserves future research.

## 4.5 Conclusion

In summary, coupling these large-scale models of current habitat type and historic transformation with smaller scale, in-depth field studies can test ecological change-based hypotheses and lead to greater understanding of plant community evolution. Results can then be re-projected onto larger scale models to aid in restoration prioritization and land management. In this way, the field studies of plant community ecology and the GIS-based remote sensing projects have the potential to develop a mutualistic relationship, enhancing each other and providing researchers with tools for a combined approach that could be much more powerful than either method alone. Given the relative ease and promise of this combination technique for assessing large areas of habitat, it will most likely continue to gain momentum in the research community. However, as illustrated by the comparison between my in-depth field study and the CASI, there definitely are limitations with current remote sensing technologies in terms of accurately representing small-scale variability. In this way, at least with current applications, there exists a definite trade-off of largeness of scale for thoroughness in plant community ecology, as there has always been in ecological studies, but there is definite potential for narrowing of this gap with further advancement in the field of remote sensing and GIS technologies in coming years.

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Appendix A: Photographs of Russian Island study sites.



**Figure A1. DIM site.**  
**Crystal Elliot in photo.**



**Figure A2. IMM site.**  
**Crystal Elliot in photo.**





Figure A3. *Lythrum salicaria* stand at IMM site.

Si Simenstad in photo.

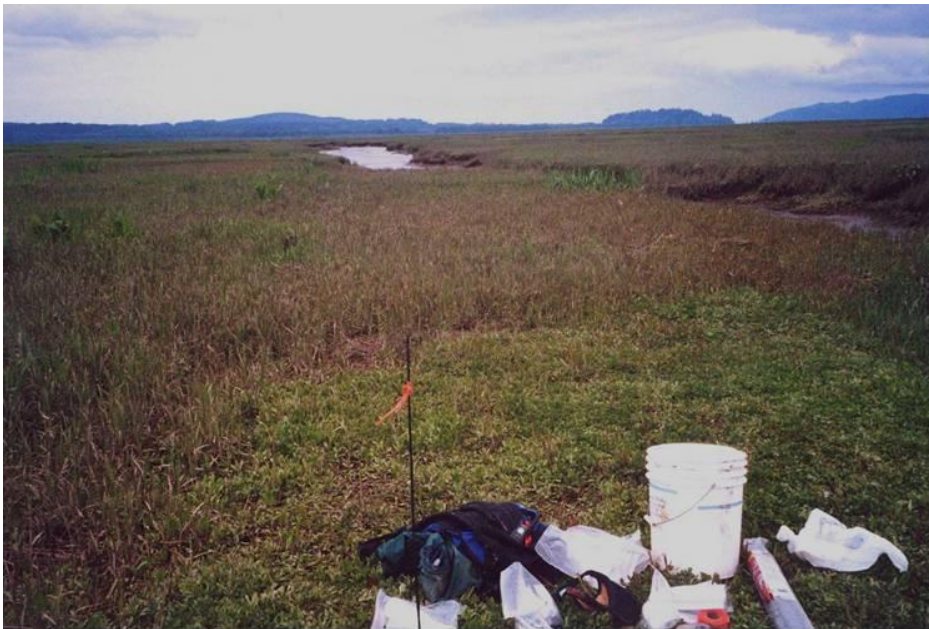


Figure A4. INT site, illustrating effects of grazing by geese.

Field materials are located in a patch in the marsh where *Carex lyngbyei* appears to have been heavily grazed by geese.



**Figure A5. STBL site.  
Crystal Elliot in photo.**



Figure A6. *Salix sitchensis* stand at STBL site.

## Appendix B: Lower Columbia River estuary wetland types from Thomas (1984).

**Brackish marshes below mean higher-high water:** This vegetation type covers approximately 600 ha in Trestle bay, Baker Bay, and Youngs Bay. In Trestle Bay, this wetland type is characterized by *Scirpus americanus*, *Carex lyngbyei*, *Agrostis alba*, *Triglochin maritimum*, *Deschampsia caespitosa*, and *Juncus balticus*. The same species characterize Baker Bay, but *Scirpus americanus* is much more prevalent. The vegetation assemblage found in Baker and Trestle Bays is widespread in other estuaries of the Pacific Northwest, and matches well with salt marsh community descriptions from Eilers (1975) and Jefferson (1975). This vegetation type in Youngs Bay is characterized by *Carex lyngbyei*, *Deschampsia caespitosa*, *Lilaeopsis occidentalis*, *Scirpus tabernaemontani*, *Scirpus acutus*, *Oenanthe sarmentosa*, and *Typha angustifolia*.

**Brackish marshes with irregular tidal inundation:** This wetland type covers approximately 140 ha in Trestle, Baker, and Youngs Bays; occurs in higher elevations and is more diverse than the previous vegetation type. This wetland type is characterized by *Aster subspicatus*, *Potentilla pacifica*, *Agrostis alba*, *Carex obnupta*, *Athyrium filix-femina*, *Oenanthe sarmentosa*, and *Lathyrus palustris*.

**Brackish water shrub/scrub wetland with irregular tidal inundation:** This vegetation type covers about 100 ha in Youngs Bay. It is characterized by a canopy of *Salix hookeriana*, *Lonicera involucrata*, *Rubus spectabilis*, *Picea sitchensis* and occasionally *Alnus rubra*. The understory comprises namely those species occurring in the previous wetland type.

**Freshwater emergent marsh with regular tidal inundation:** This wetland type covers approximately 2,000 ha between RM-17 and 40 (km 27.4 and 64.4), making it more common than the other vegetation types, especially in Cathlamet Bay. This habitat type is dominated by *Carex lyngbyei*, which is unusual because this species is usually associated with brackish conditions. Another unusual common species is *Equisetum fluviatile*, which is at the southern limit of its range and often forms large patches of dense clonal growth up to 100 m in diameter. The vegetation here is highly diverse, and other common species include, *Juncus oxymersis*, *Eleocharis palustris*, *Deschampsia caespitosa*, *Sium suave*, *Boltonia asteroides*, *Bidens cernua*, *Sagittaria latifolia*, *Alisma plantago-aquatica*, *Scirpus tabernaemontani*, and *Scirpus acutus*.

**Freshwater emergent marsh with irregular tidal inundation:** This vegetation type covers about 560 ha between RM-17 and 40 (km 27.4 and 64.4); high marsh; extremely diverse and variable in local composition, with distinct communities hard to define; extensive in Cathlamet Bay. Many of the species in the previous wetland type are found here, as well as *Lotus corniculatus*, *Festuca arundinacea*, and other non-natives. *Impatiens noli-tangere*, an annual, is also highly common.

***Freshwater shrub-dominated wetlands with irregular tidal inundation:*** This wetland type covers approximately 1,800 ha between RM-17 and 40 (km 27.4 and 64.4). The widespread dominant species in this vegetation type is *Salix sitchensis*, while *Salix lasiandra*, *Cornus stolonifera*, and *Spiraea douglasii* are also common.

***Freshwater forested wetlands with irregular tidal inundation:*** This vegetation type covers about 650 ha between RM-17 and 40 (km 27.4 and 64.4), and it occurs as a mosaic with shrub-dominated swamps. The dominant species in this habitat type is *Picea sitchensis*, while the shrubs mentioned in the previous wetland type are also important.

## Appendix C: Lower Columbia River estuary wetland types from Macdonald (1984).

**Brackish low marshes:** Usually only one or two species account for the majority of cover and biomass. Dominants: *Carex lyngbyei*, *Scirpus americanus*, and *Agrostis alba*. Other species: *Triglochin maritimum*, *Fucus distichus edentatus*, *Typha angustifolia*, *Deschampsia caespitosa*, *Lilaeopsis occidentalis*, *Potentilla pacifica*, *Scirpus tabernaemontani*, *Zannichella palustris*, Low salinity: *Alisma plantago-aquatica*, *Eleocharis palustris*, *Equisetum* sp., *Oenanthe sarmentosa*, *Scirpus microcarpus*, and *Typha latifolia*,

**Brackish high marshes:** More complex than brackish low marshes, with increasing numbers of species at higher elevations. Dominants: *Carex lyngbyei*, *Agrostis alba*. Other species: *Potentilla pacifica*, *Lathyrus palustris*, *Juncus balticus*, *Aster subspicatus*, *Carex obnupta*, *Festuca arundinacea*, *Oenanthe sarmentosa*, *Rumex crispus*, and *Vicia gigantea*.

**Freshwater low marshes:** Much more diverse and variable than brackish marshes. Dominant: *Carex lyngbyei*. Other species: *Aster subspicatus*, *Deschampsia caespitosa*, *Alisma plantago-aquatica*, *Elodea Canadensis*, *Mimulus guttatus*, *Sagittaria latifolia*, *Sium suave*, *Callitriche* sp., *Myosotis laxa*, *Phalaris arundinacea*, *Lilaeopsis occidentalis*, *Scirpus tabernaemontani*, *Juncus balticus*, *Eleocharis palustris*, *Juncus oxymersis*, *Polygonum hydropiperoides*, *Littorella* sp., and *Ranunculus* sp.

**Freshwater high marshes:** Much more diverse and variable than brackish marshes. Dominant: *Carex lyngbyei*. Other species: *Agrostis alba*, *Lotus corniculatus*, *Potentilla pacifica*, *Caltha asarifolia*, *Equisetum fluviatile*, *Festuca arundinacea*, *Platanthera dilata*, *Rumex crispus*, *Oenanthe sarmentosa*, *Mentha* sp., *Lysichiton americanus*, *Typha latifolia*, and other species found in the freshwater low marshes.

**Brackish scrub-shrub wetlands:** Rare habitat. Dominants: *Salix hookeriana*, *Lonicera involucrata*, *Rubus spectabilis*, *Picea sitchensis*. Other species: *Alnus rubra*.

**Freshwater scrub-shrub wetlands:** Dominant: *Salix sitchensis*. Other species: *Salix lasiandra*, *Cornus stolonifera*, and *Spiraea douglasii*. Understory: *Lysichiton americanus* and other freshwater marsh species

**Freshwater forested wetlands:** Rare habitat with hummock-hollow topography. Dominant: *Picea sitchensis*. Other species: shrub species previously mentioned, as well as many upland forest species occurring on the hummocks and wetland species in the hollows.

## Appendix D: Equations used in grain size analysis calculations.

The clay fraction as a percentage was calculated as follows:

$$\% \text{ clay} = P_{2\mu_m} = m \ln (2 / X_{24}) + P_{24} \quad (1)$$

$X_{24}$  = mean particle diameter in suspension at 24 hr (see Equation 2)

$P_{24}$  = summation percentage at 24 hr (see Equation 3)

$m = (P_{1.5} - P_{24}) / \ln (X_{1.5} / X_{24})$ ; slope of the summation percentage curve between  $X$  at 1.5 hr and  $X$  at 24 hr

$X_{1.5}$  = mean particle diameter in suspension at 1.5 hr

$P_{1.5}$  = summation percentage at 1.5 hr

Mean particle diameter in suspension at a given time from initial mixing is determined as follows:

$$X = \theta t^{-0.5} \quad (2)$$

$\theta$  = pre-tabulated sedimentation parameter as a function of hydrometer readings,  $R$ , for

ASTM 152 hydrometer (Day 1956)

$t$  = time from initial mixing; minutes

Summation percentage at a given time from initial mixing was calculated as follows:

$$P = (C / C_o) * 100 \quad (3)$$

$C = (\text{concentration of soil in suspension in } g L^{-1}) = R - R_L$ ;  $R$  is the uncorrected hydrometer reading in  $g L^{-1}$ , and  $R_L$  is the hydrometer reading of a solution devoid of soil

$C_o$  = weight of the soil sample used in analysis

The sand fraction was calculated using the same procedure as for  $P_{2\mu_m}$ , but using the 30 s and 1 min readings instead of the 1.5 hr and 24 hr readings. This resulting  $P_{50\mu_m}$  was then subtracted from 100 to obtain sand percentage.

The silt fraction as a percentage was calculated as follows:

$$\% \text{ silt} = 100 - (\% \text{ sand} + \% \text{ clay}) \quad (4)$$

A correction was necessary to achieve an accurate determination of grain size because the ASTM hydrometer readings were standardized for 20°C, and fluctuating temperatures in the laboratory (between 18 and 30°C) potentially affected readings. The changing temperature of the solution in the graduated cylinders caused its density to change, resulting in unstandardized hydrometer readings. This inconsistency required that a regression be performed to correct readings. Two regressions were performed to ensure accuracy: two graduated cylinders containing a warm sodium hexametaphosphate solution of the same concentration as used in the grain size analysis were placed in the cold room (3°C), and the temperature and density (with the same hydrometer as used in the analyses) were measured periodically as the solution temperature dropped (from 38-15°C). Readings were entered into Microsoft<sup>®</sup> Excel and regressions were calculated ( $r^2_1 = 0.9891$  and  $r^2_2 = 0.9906$ ), indicating that the relationship between temperature and density was linear within this temperature range. The resulting average slope was  $-0.3365$ , indicating that for every 1°C increase in temperature, there would be a  $-0.3365 \text{ g L}^{-1}$  change in density. This relationship was used to convert the original hydrometer readings to their values at 20°C.



## Appendix E: Discussion of multivariate data analysis methods.

Ordination is a method of data reduction that arranges vegetation samples in relation to each other in terms of species composition and/or environmental controls (Kent and Coker 1992). In this way, ordination provides insight into the organization of high-dimensional community data by seeking to display the strongest structure through arrangement of the data on a grid along axes that represent underlying environmental controls (McCune and Grace 2002). In general, the axes in ordination graphs are arranged in decreasing order of importance, with the first axis explaining more variation than the second, and so on (Kent and Coker 1992). Eigenvalues are a numeric representation of the relative contribution by each axis (component) to the explanation of the total variation in the data. In this way, the size of the eigenvalue for a given axis is a direct indication of the importance of that axis in explaining the total variation within the data set. Distances between species and/or between stands on the graph approximate their degree of similarity in ecological space (i.e., quadrats containing dissimilar species compositions will be positioned far away from each other on the graph). The terms “stand” and “plot” are synonymous for a sampling quadrat. DCA (Hill and Gauch 1980) is a widely used and accepted indirect [not constrained by known values for environmental gradients and does not use environmental data to order the vegetation samples] ordination technique (Kent and Coker 1992). The assumption is made that analysis of the variation in floristics will inevitably reflect variation in the environment. Overlays (joint plots) of measured environmental factor data can further aid the interpretation of species-environment relationships.

DCA is based on correspondence analysis (reciprocal averaging), an eigenanalysis technique where compositional dissimilarity is measured using the chi-square distance measures and samples (plots) are weighted by their species totals (McCune and Grace 2002). However, DCA attempts to correct the two main faults of correspondence analysis: compression of the first-axis ends relative to the axis middle and dependence of the second axis on the first (making the second axis sometimes merely a quadratic reproduction of the first) (Kent and Coker 1992, Peck 2004). DCA seeks to correct these faults by rescaling the first axis and detrending the second axis (eliminating the “arch” created by the quadratic). Some criticize the validity of this “fix” because it mathematically forces species relationships into a more uniform organization, as well as failing to eliminate the reliance of the second axis on the first (Beals 1984, Jackson and Somers 1991, Legendre and Legendre 1999, McCune and Grace 2002, Minchin 1987, ter Braak 1986). However it is accepted that if the variability in a community data set is mostly explained by a single gradient (as is the case in this study), or at least a predominant one, then validity of reciprocal averaging, and therefore DCA, is restored (Peck 2004). Another criticism imposed on DCA is the use of a chi-square distance measure,

which gives high weight to species whose total abundance in the data matrix is low (McCune and Grace 2002). Due to the heavy criticism this method receives, I opted to employ an additional ordination method, Nonmetric Multidimensional Scaling (NMS) [medium setting] to verify the results from the DCA ordination. In both, analyses, default settings were used (McCune and Mefford 1999).

NMS (Anderson 1971, Kruskal 1964 a,b, Shepard 1962a,b) is touted by McCune and Grace (2002) as being “the most generally effective ordination method for ecological community data, and should be the method of choice” (p125). NMS uses rank order information in a dissimilarity matrix (using Sorenson distance) to place quadrats (or species) in a low dimensional ordination space such that the interpoint distance in the ordination have the same rank order as do the interpoint dissimilarities in the dissimilarity matrix (true ecological dissimilarities) calculated between all pairs of quadrats or all pairs of species, to as great a degree as possible (Kent and Coker 1992, Peck 2004). Monotonicity describes the rank order that exists in the original data set, and stress (departure from monotonicity) is defined as how closely the rank order achieved by the ordination matches the monotonic set (McCune and Grace 2002). The procedure of NMS is to use multiple iterations of this ordination to find the solution that reduces this stress as much as possible while utilizing as few axes as possible (Kent and Coker 1992, Peck 2004). NMS is thus a technique of data reduction that organizes species (or stands) on the basis of their ecological dissimilarities, meanwhile retaining as much of the structure of the full dataset as possible (Peck 2004).

TWINSPAN (Gauch and Whittaker 1981, Hill 1979) is a widely-used polythetic divisive classification technique that simultaneously classifies species and sample units on the basis of quadrat data in the form of species presence-absence or pre-defined classes representing degree of dominance or percent cover (pseudospecies cut levels). TWINSPAN ordines stands using reciprocal averaging (correspondence analysis) on the basis of species data and proceeds to iteratively divide the stands into discrete groups on the basis of similarities in species composition (McCune and Grace 2002). These two groups then proceed to be successively divided on the basis of a reclassification using species with maximum value for indicating the poles of the ordination axes. The dichotomous dividing of groups continues until a set number of divisions are attained or the researcher determines that the divisions are no longer resulting in ecologically meaningful groups (Gauch 1982, Kent and Coker 1992). Eigenvalues are given for each division, indicating the degree of difference between the created groups. Groups were chosen on the basis of similar dominant species and similar species composition. A powerful result of the analysis is the Two-way Table, a data matrix that allows the user to visualize divisions in stands/plots on the basis of variation in species composition, as well as the divisions of species groups. The table is ordered, meaning that the species on either end of the list are often found in completely different environments and species that are next to one another on the

list are often found in the same or similar environments (Ewing 2000). This helps the investigator to construct a model for community organization and allowing for the integration of field knowledge to aid in the identification of underlying environmental gradients that drive the floristic organization. The resulting groups can then be projected onto the DCA ordination to further aid in the visualization of species assemblage organization in relation to each other and the underlying environmental gradients. The default settings of TWINSpan in PC-ORD (McCune and Mefford 1999) were used in this study with a pseudospecies cut level of 0.00 (for presence-absence).

Since TWINSpan utilizes correspondence analysis (reciprocal averaging) for its ordination component, it receives that same criticism as DCA and its parent method (McCune and Grace 2002). However, as with DCA, it is accepted that results from this analysis are reliable if an ordination illustrates that the majority of the variability in the data is represented by only one axis (Peck 2004), which, as said before, is the case with the data in this study.

Despite the documented weaknesses of DCA compared to NMS, I chose to use DCA to facilitate portrayal of plant community organization and relationships to environmental variables because the DCA results were similar to the NMS results, but were more straightforward to interpret and made more sense ecologically (i.e., the joint plots representing environmental gradients appeared much more meaningful in the DCA graphs and the DCA ordination was more consistent with what I saw in the field). Also, as mentioned earlier, since the majority of variation in my dataset was explained by only one axis, the shortcomings of DCA and reciprocal averaging did not have a large effect on the ordination results.

## Appendix F: Equations used in diversity calculations.

Average alpha ( $\alpha$ ) at a given site is calculated as:

$$\text{Mean } \alpha = (\Sigma s)/n$$

$\Sigma s$  = sum of the total number of species across all sample units

$n$  = number of sample units

The Shannon Diversity Index is calculated as (Shannon 1948):

$$H' = - \Sigma (\text{from } i=1 \text{ to } s) \text{ of } p_i \log_{10} p_i$$

$H'$  = diversity

$s$  = the number of species

$p_i$  = the proportion of individuals (representation of percent cover)

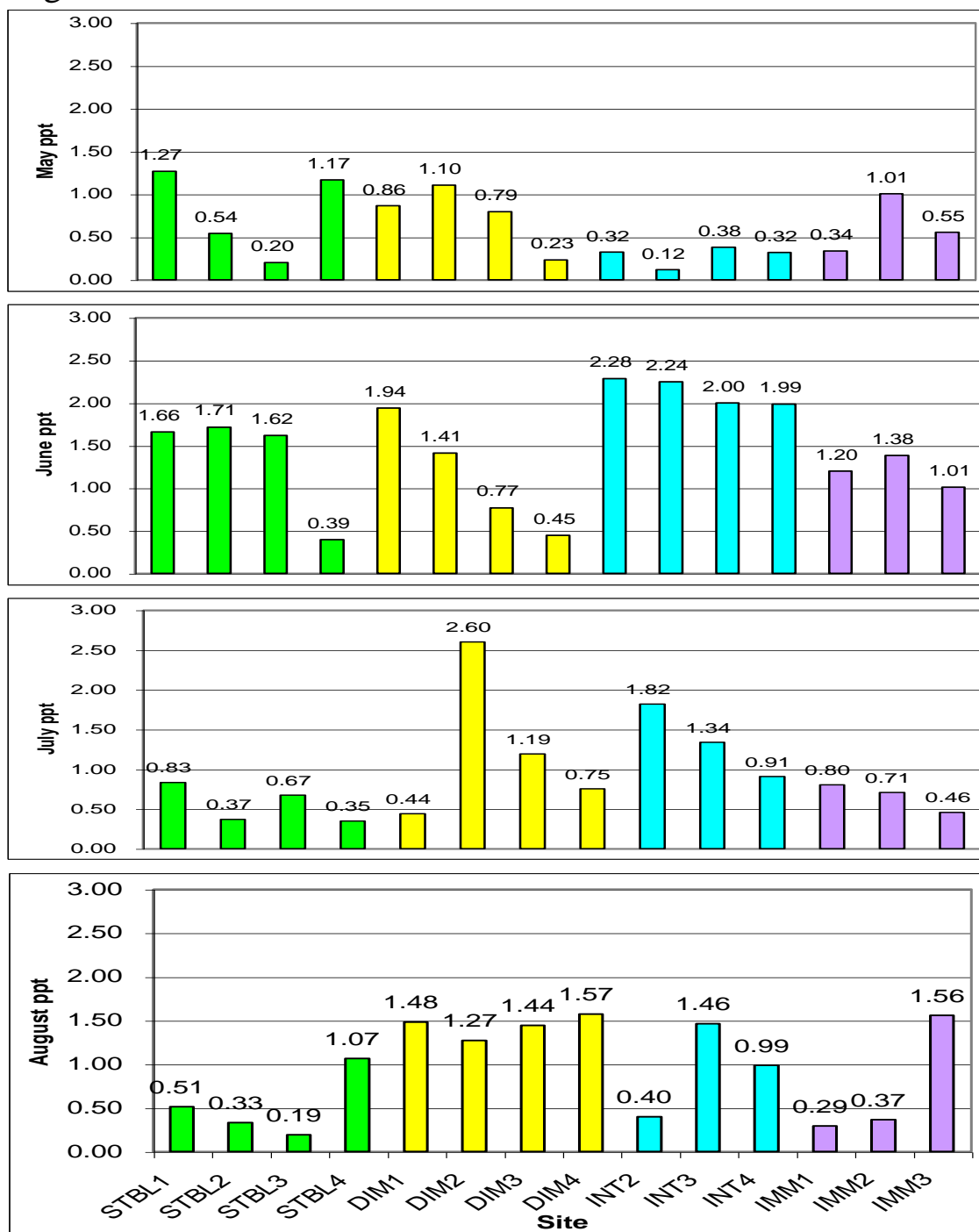
Pielou's  $J$ , a measure of evenness is calculated as (Pielou 1969):

$$J = H' / (\log_{10} s)$$

$H'$  = Shannon's diversity

$s$  = the number of species

Appendix G. Soil pore salinity measurements at Russian Island study site sampling stations for the months of May, June, July, and August.



## Appendix H: Russian Island study plant species list and species characteristics.

**Table H1. Russian Island study plant species list and species characteristics.**

Respective family, species code, Region 9 wetland indicator status (as determined from USDA, NRCS 2004), salinity tolerance (as determined from Guard 1995, Hutchinson 1988a, Klinka et al. 1989), general Pacific Northwest (PNW) habitat (as determined from Guard 1995, Klinka et al. 1989, Macdonald 1984, Pojar and MacKinnon 1994, and UW 2004), and observed Russian Island (RI) habitat for species surveyed at Russian Island study sites. See Table H2 for definitions of terms in “wetland indicator status” column. See Table H3 for definitions of terms in “salt tolerance” column. See Table H4 for definitions of terms in “RI habitat” column.

Species	Family	Code	WL indicator status	Salt tolerance	General PNW habitat	RI habitat
<i>Agrostis stolonifera</i> (creeping bentgrass)	Poaceae	AGST	FAC	M	Very common in moist to wet fields, lawns, ditches, meadows; variable soils	H
<i>Aster subspicatus</i> (Douglas' aster)	Asteraceae	ASSU	FACW	M	Common in moist to wet prairies, meadows, esp. common in coastal marshes; silty to loamy soils	M
<i>Athyrium filix-femina</i> (lady fern)	Dryopteridaceae	ATFI	FAC+	S	Common in moist to wet forests, swamps, stream-banks; mucky to loamy soils	SS
<i>Callitriche</i> spp. (water-starworts)	Callitrichaceae	CASP	OBL	S	Common in lakes, ponds, ditches; floating habit; silty soils	L (extreme LM and HMD)
<i>Caltha palustris</i> sp. <i>asarifolia</i> (yellow marsh marigold)	Ranunculaceae	CAPA	OBL	VS	Low-elevation swamps, bogs, marshes; rare south of B.C.; nutrient-rich loamy soils	M
<i>Carex lyngbyei</i> (Lyngby's sedge)	Cyperaceae	CALY	OBL	T	Often the dominant species in coastal tidal marshes, estuarine meadows, brackish marshes; fine-sand to silt soils	U (not SS)
<i>Claytonia sibirica</i> (candy-flower, Siberian miner's lettuce)	Portulacaceae	CLSI	FAC	S	Moist, often shady stream-banks, moist forests; nutrient-rich loamy soils	M
<i>Deschampsia caespitosa</i> (tufted hairgrass)	Poaceae	DECE	FACW	T	Common in coastal tidal marshes, wet prairies, beaches; fine-sand to silt soils	M
<i>Eleocharis palustris</i> (creeping spike-rush)	Cyperaceae	ELPA	OBL	MT	Common in standing water in wet prairies, brackish tidal marshes, shorelines, ditches; fine sand to silt soils	L (LM and HMD)
<i>Epipactis gigantea</i> Dougl. ex Hook. (stream orchid, giant helleborine)	Orchidaceae	EPGI	FACW+	S	Rare, most common along Columbia River, in freshwater marshes, along streambanks and springs; loamy soils	H

**Table H1 (continued).**

<i>Equisetum fluviatile</i> (water horsetail)	Equisetaceae	EQFL	OBL	VS	Common in extremely wet areas of marshes, lake edges, ditches; silty to loamy soils	U (not ML)
<i>Festuca arundinacea</i> (tall fescue)	Poaceae	FEAR	FAC-	MT	Common non-native in moist fields, pastures, prairies	SS
<i>Galium aparine</i> (common bedstraw, cleavers)	Rubiaceae	GAAP	FACU	S	Very common in moist areas of forests or in fields; tolerant of variable soil conditions	H
<i>Hieracium</i> sp. (hawkweed)	Asteraceae	HISP	NI	n/a	Common weed in urban areas, roadsides, lawns; tolerant of low nutrient sites	M
<i>Hypericum anagalloides</i> (bog St. John's wort)	Clusiaceae	HYAN	OBL	S	Common in moist prairies, wet ditches, sphagnum bogs; fine-sand, silt, loam soils	H
<i>Impatiens noli-tangere</i> (common touch-me-not, jewelweed)	Balsaminaceae	IMNO	FACW	VS	Moist forests, streambanks; nutrient-rich loamy soils	H
<i>Iris pseudacorus</i> (yellow flag iris)	Iridaceae	IRPS	OBL	VS	Common non-native on shores of lakes, along streambanks, and in ditches; silty to sandy soils	H
<i>Juncus effusus</i> (soft rush)	Juncaceae	JUEF	FACW	S	Very common in wet prairies, wet pastures, fields; variable soils; tolerates low nutrient conditions	H
<i>Juncus oxymiris</i> (pointed rush)	Juncaceae	JUOX	FACW+	S	Common in wet meadows, lakeshores, standing water in ponds; fine-sand to silt soils	ML
<i>Lathyrus nevadensis</i> (purple peavine)	Fabaceae	LANE	NI	n/a	Common in moist to dry forests and clearings; variable soils; N-fixer	H
<i>Lilaeopsis occidentalis</i> (western lilaeopsis)	Apiaceae	LIOC	OBL	T	Common in most maritime habitats; mudflats, tidal marshes, sandy beaches; fine-sand to silt soils	L
<i>Lotus corniculatus</i> (bird's foot trefoil)	Fabaceae	LOCO	FAC	MT	Common non-native in wetland prairies, marshes, but can be found on drier disturbed sites; weedy	H
<i>Lupinus polyphyllus</i> (large-leaf lupine)	Fabaceae	LUPO	FAC+	S	Common in wetland prairies, along streams, and disturbed sites; variable soils; N-fixer	M
<i>Lysichiton americanus</i> (skunk cabbage)	Araceae	LYAM	OBL	VS	Common in wooded wetland communities, swamps, marshes; mucky soils	H (but also in HMD)
<i>Lycopus americanus</i> (cutleaf horehound)	Lamiaceae	LYAE	OBL	S	Common in wet meadows, marshes, and along stream edges; silt, clay, to loam soils	ML

Table H1 (continued).

<i>Lythrum salicaria</i> (purple loosestrife)	Scrophulariaceae	LYSA	OBL	MS	Common non-native in freshwater wetland communities; variable soils; highly invasive	U (not ML or SS)
<i>Mentha arvensis</i> (field mint)	Lamiaceae	MEAR	FACW-	VS	Common in wet meadows and prairies, ditches, seeps, lake shores; silt, clay, to loam soils	M
<i>Mimulus guttatus</i> (seep-spring monkey flower)	Scrophulariaceae	MIGU	OBL	S	Wet prairies and meadows, marshes, streambanks; silt, clay, to loam soils	M
<i>Myosotis laxa</i> (small-flowered forget-me-not)	Boraginaceae	MYLA	OBL	VS	Very common in wet prairies, vernal pools, and along edges of ponds; silt, clay to loam soils	U (incl. HMD, not SS)
<i>Oenanthe sarmentosa</i> (water parsley)	Apiaceae	OESA	OBL	MT	Common in extremely wet areas of marshy shore communities and wooded wetlands; silty soils	ML (often in HMD)
<i>Phalaris arundinacea</i> (reed canary grass)	Poaceae	PHAR	FACW	MT	Extremely common non-native in wetland prairie communities and streambanks; highly invasive	E (incl. HMD)
<i>Platanthera dilata</i> (white bog orchid)	Orchidaceae	PLDI	FACW+	S	Fairly uncommon, but found in swamps, bogs, fens, marshes, wet forests; silt, clay to loam soils	M
<i>Poa trivialis</i> (rough bluegrass)	Poaceae	POTR	FACW-	S	Common in wet prairies, moist meadows, wooded wetlands; silt, clay, to loam soils	H
<i>Polygonum hydropiperoides</i> (waterpepper)	Polygonaceae	POHY	OBL	S	Common in extremely wet areas of marshes, lake edges with fluctuating water levels; silty, mucky soils	L (LM and HMD)
<i>Potentilla pacifica</i> (Pacific silverweed)	Rosaceae	POPA	OBL	MT	Common in coastal wetlands, marshes, beaches and dunes; sandy to silty soils	M
<i>Ranunculus orthorhynchus</i> (straight-beak buttercup)	Ranunculaceae	RAOR	FACW-	S	Common in wet prairies, moist meadows, along streambanks; clay, silt, to loam soils	M
<i>Rubus discolor</i> (Himalayan blackberry)	Rosaceae	RUDI	FACU	nf	Extremely common non-native in disturbed areas and streambanks; highly invasive	SS
<i>Sagittaria latifolia</i> (wapato)	Alismataceae	SALA	OBL	S	Fairly rare, but found in extremely wet areas in tidal freshwater marshes; silty, mucky soils	L (most often in HMD)



**Table H1 (continued).**

<i>Salix lasiandra</i> (Pacific willow)	Salicaceae	SALC	FACW+	S	Common in scrub-shrub wetlands, swamps; variable soils (can establish on extremely coarse soils, but prefers clay loams)	H
<i>Salix sitchensis</i> (sitka willow)	Salicaceae	SASI	FACW	S	Common in scrub-shrub wetlands, swamps, streambanks; variable soils (can establish on coarse soils, but prefers clay loams)	SS
<i>Scirpus microcarpus</i> (small-fruited bulrush)	Cyperaceae	SCMI	OBL	S	Common in swamps, marshes, along streambanks; silty, mucky, nutrient-rich soils	L (HMD)
<i>Scirpus tabernaemontani</i> (soft-stem bulrush)	Cyperaceae	SCTA	OBL	MS	Fairly common in inundated areas of brackish marshes, along lakes, and in prairie wetlands; silty soils	L (HMD and LM)
<i>Sium suave</i> (water parsnip)	Apiaceae	SISU	OBL	S	Common in marshes, riverbanks, lake shores; silty soils	ML
<i>Solanum dulcamara</i> (European bittersweet)	Solanaceae	SODU	FAC+	nf	Common non-native in disturbed areas, roadsides, thickets; variable soils	SS
<i>Trifolium wormskjoldii</i> (spring-bank clover)	Fabaceae	TRWO	FACW+	MT	Common in wet meadows, pastures; silt, clay, loam soils	H
<i>Typha latifolia</i> (cattail)	Typhaceae	TYLA	OBL	MS	Common in shallow water of marshes, lakeshores, ditches; silty, mucky soils	M
<i>Veratrum viride</i> (Indian hellebore)	Liliaceae	VEVI	FACW	nf	Common in wet thickets and cold wet meadows, often subalpine; clay, silt, to loam soils	H

**Table H2. Species wetland indicator status for Region 9.****(USFS 1996)**

Code	Wetland Type	Comment
OBL	Obligate wetland	Occurs almost always (estimated probability 99%) under natural conditions in wetlands
FACW	Facultative wetland	Usually occurs in wetlands (estimated probability of 67%-99%), but occasionally found in non-wetlands
FAC	Facultative	Equally likely to occur in wetlands or non-wetlands (estimated probability 34%-66%)
FACU	Facultative upland	Usually occurs in non-wetlands (estimated probability 67%-99%), but occasionally found in wetlands (estimated probability 1%-33%)
UPL	Obligate upland	Occurs in wetlands in another region, but occurs almost always (estimated probability 99%) under natural conditions in non-wetlands in the region specified (9 for WA)
NI	No indicator	Insufficient information was available to determine an indicator status
* A positive (+) or negative (-) sign is used with the Facultative Indicator categories to more specifically define the regional frequency of occurrence in wetlands. The positive sign indicates a frequency toward the higher end of the category (more frequently found in wetlands), and the negative sign indicates a frequency toward the lower end of the category (less frequently found in wetlands).		

**Table H3. Species salinity tolerance codes.****(adopted from Hutchinson 1988a)**

Code	Tolerance rating	Approx. max. salinity tolerance range (ppt)
T	Tolerant	16-20
MT	Moderately tolerant	10-16
MS	Moderately sensitive	6-10
S	Sensitive	0.5-6
VS	Very sensitive	0-0.5
nf	not found	-

**Table H4. Russian Island habitats.**

(from field observations and TWINSPAN classification: combination of elevation and developmental stage)

Code	Habitat elevation	Description
SS	scrub-shrub	Areas of characterized by the highest elevations; scrub-shrub habitat
H	high	Areas of high marsh at higher elevations (second most common habitat type on island)
M	mid	Areas of high marsh at mid elevations (most common habitat type on island)
ML	mid-low	Higher areas of low marsh (LM) [adjacent to base of tidal channel or at low elevations found at IMM site], high marsh depressions (HMD), or areas of low elevation high marsh
L	low	Areas of low marsh (adjacent to base of tidal channel or at low elevations found at IMM site) or high marsh depressions
U	ubiquitous	Species not characterizing one particular group or another; often found in many groups (e.g. CALY)

## Appendix I: TWINSPAN Two-Way Ordered Table summary for species surveyed at Russian Island study sites.

The Two-way Ordered Table is another powerful result of the TWINSPAN analysis, which arranges species on the basis of their similarities in occurrence, with species found on either end of the list occurring in very different environments from each other. In the constructed summary of the two-way table, species occurring on the top of the list are found at lower elevation sites, and those occurring at the bottom of the list are found at higher elevation sites. Their frequency of occurrence in each of the five TWINSPAN classes is also shown.

**Table II. TWINSPAN species classification summary.**

List of species (see Appendix H to get species and common names from code) found at study sites on Russian Island, Columbia River estuary. Species have been ranked by TWINSPAN classification program so that those generally found at the higher sites occur at the bottom of the list and those generally found at the lower elevation sites occur at the top. Frequency of occurrence in five general wetland assemblage types generated by TWINSPAN analysis (low [L], mid-low [ML], mid [M], high [H], and scrub-shrub [SS]) is shown as a percentage. Numbers of plots in each assemblage type are as follows: L=24, ML=10, M=27, H=20, SS=5.

<b>SPECIES</b>	<b>L</b>	<b>ML</b>	<b>M</b>	<b>H</b>	<b>SS</b>
CASP	46	0	0	5	0
POHY	29	60	4	5	0
SCTA	21	0	0	5	0
LIOC	8	0	4	0	0
ELPA	8	0	0	0	0
LYAE	42	40	7	0	0
SALA	21	40	0	0	0
SCMI	8	0	0	0	0
JUOX	17	40	15	0	0
OESA	33	70	30	0	0
CALY	71	100	96	25	0
LYSA	21	0	22	15	0
CAPA	4	70	22	5	0
RAOR	4	10	41	5	0
DECE	46	20	85	0	0
HISP	0	0	56	0	0
MEAR	0	10	33	0	0
MIGU	0	20	48	0	0
TYLA	0	0	19	0	0
ASSU	0	10	22	0	0
CLSI	0	0	7	0	0
LUPO	0	0	7	0	0

**Table I1 (continued).**

PLDI	0	0	26	0	0
SISU	13	0	26	0	0
POTR	0	0	48	20	0
SALC	0	40	30	25	0
TRWO	0	0	11	5	0
VEVI	0	0	19	5	0
EPGI	0	0	11	10	0
EQFL	46	0	63	70	80
MYLA	25	100	52	65	0
POPA	0	50	63	55	0
GAAP	0	10	30	45	20
LOCO	0	50	7	40	0
HYAN	0	20	0	20	0
LANE	0	0	4	5	0
LYAM	4	0	19	35	80
AGST	0	0	4	15	0
IRPS	0	0	15	45	0
JUEF	0	0	0	15	0
IMNO	0	20	0	35	20
SODU	0	0	0	10	20
ATFI	0	0	0	0	20
FEAR	0	0	0	0	20
RUDI	0	0	0	0	60
SASI	0	0	4	10	100
PHAR	46	10	19	70	40

## Appendix J: DCA ordinations using Axis 3.

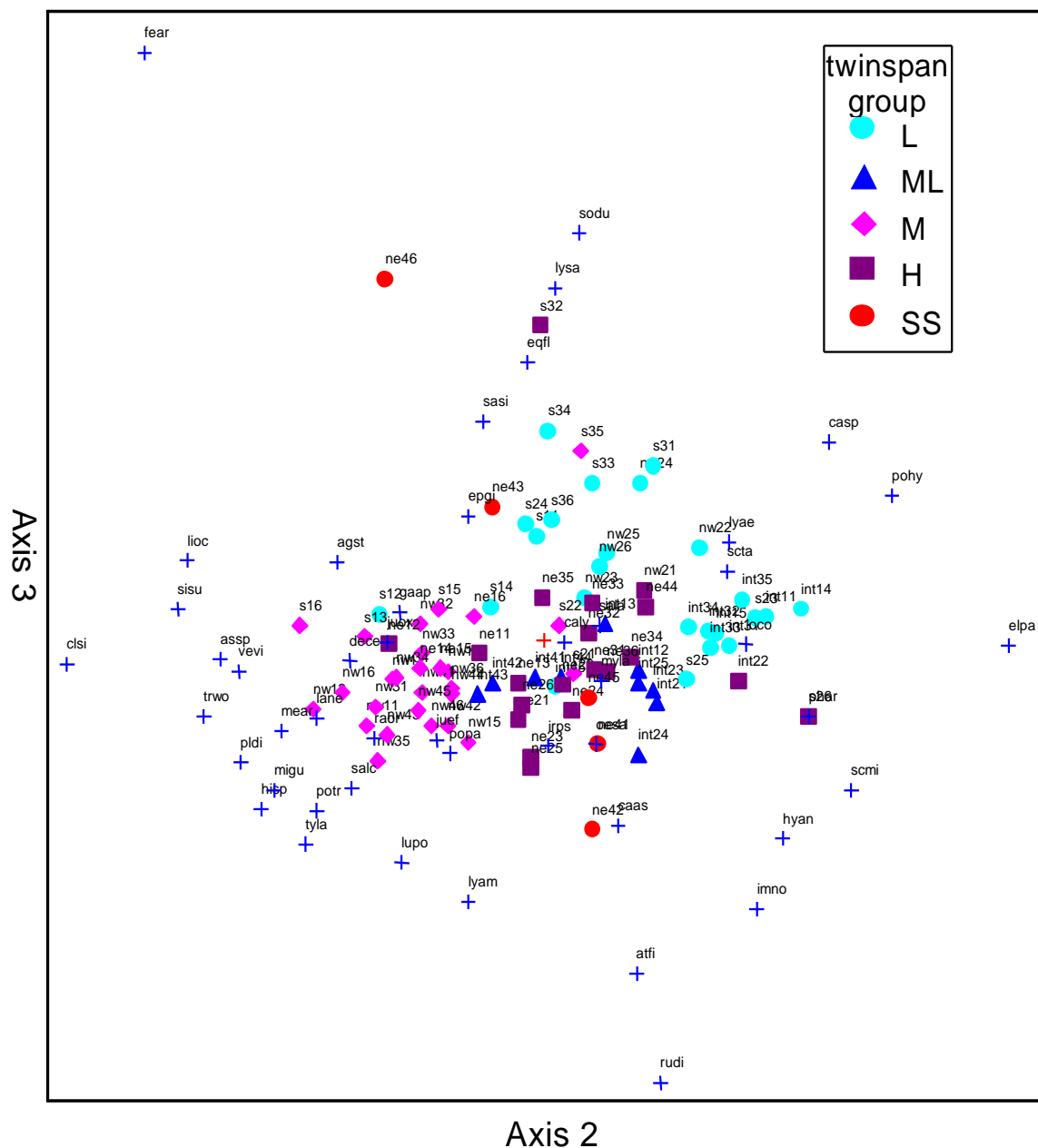


Figure J1. DCA ordination diagram of stands and species at Russian Island sites for Axis 2 vs. Axis 3.

Species locations on the ordination diagram are identified by the first two letters of genus and the first two letters (or unique letters if the first two are the same for two species) of the specific epithet (see Appendix H for codes). Stands are shape coded and color coded according to TWINSpan group [L, ML, M, H, SS]. Individual plots are labeled with their location code (e.g. nw) followed by the sampling station number, followed by the quadrat number.

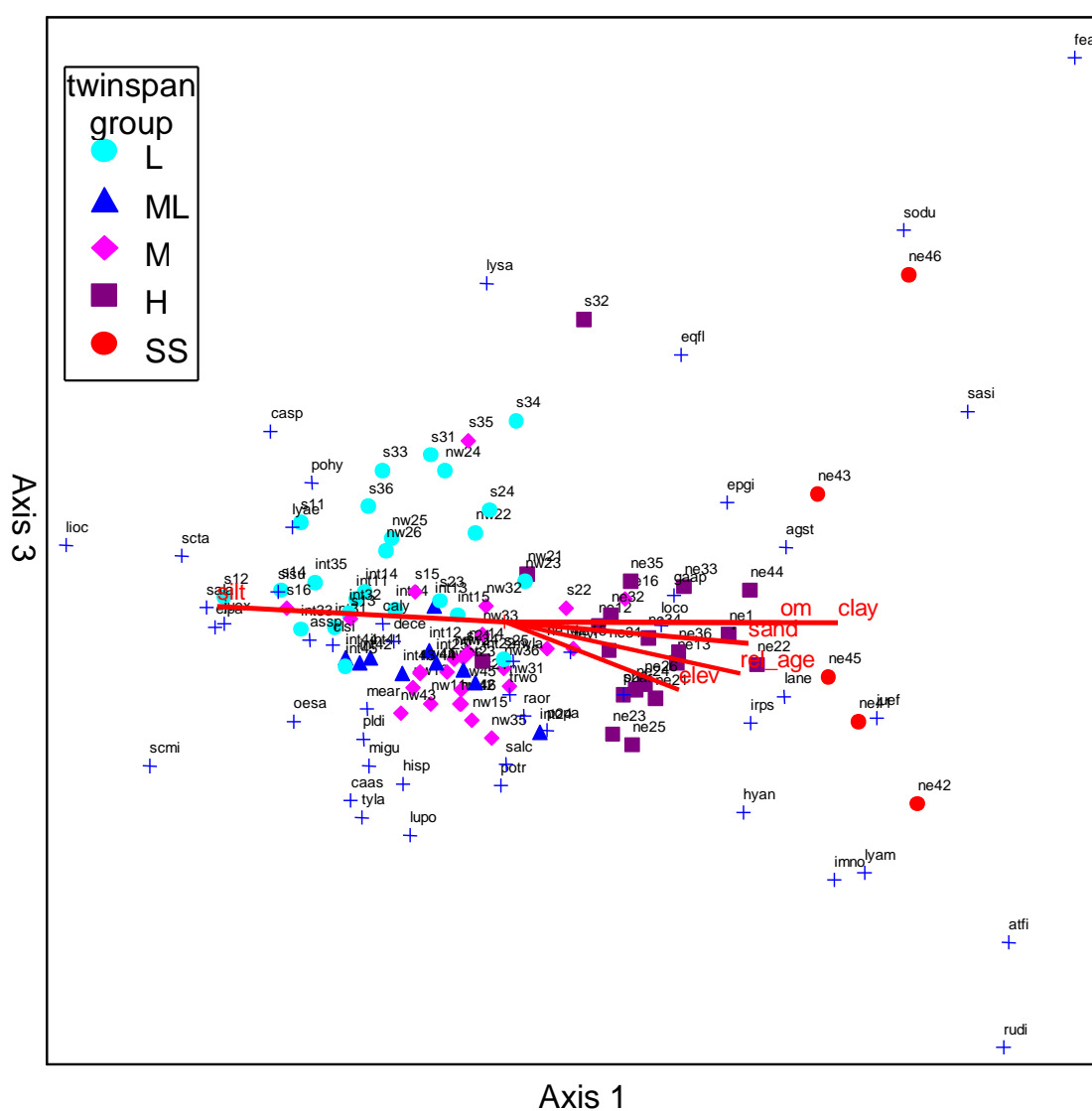


Figure J2. DCA ordination diagram of stands and species at Russian Island sites for Axis 1 vs. Axis 3.

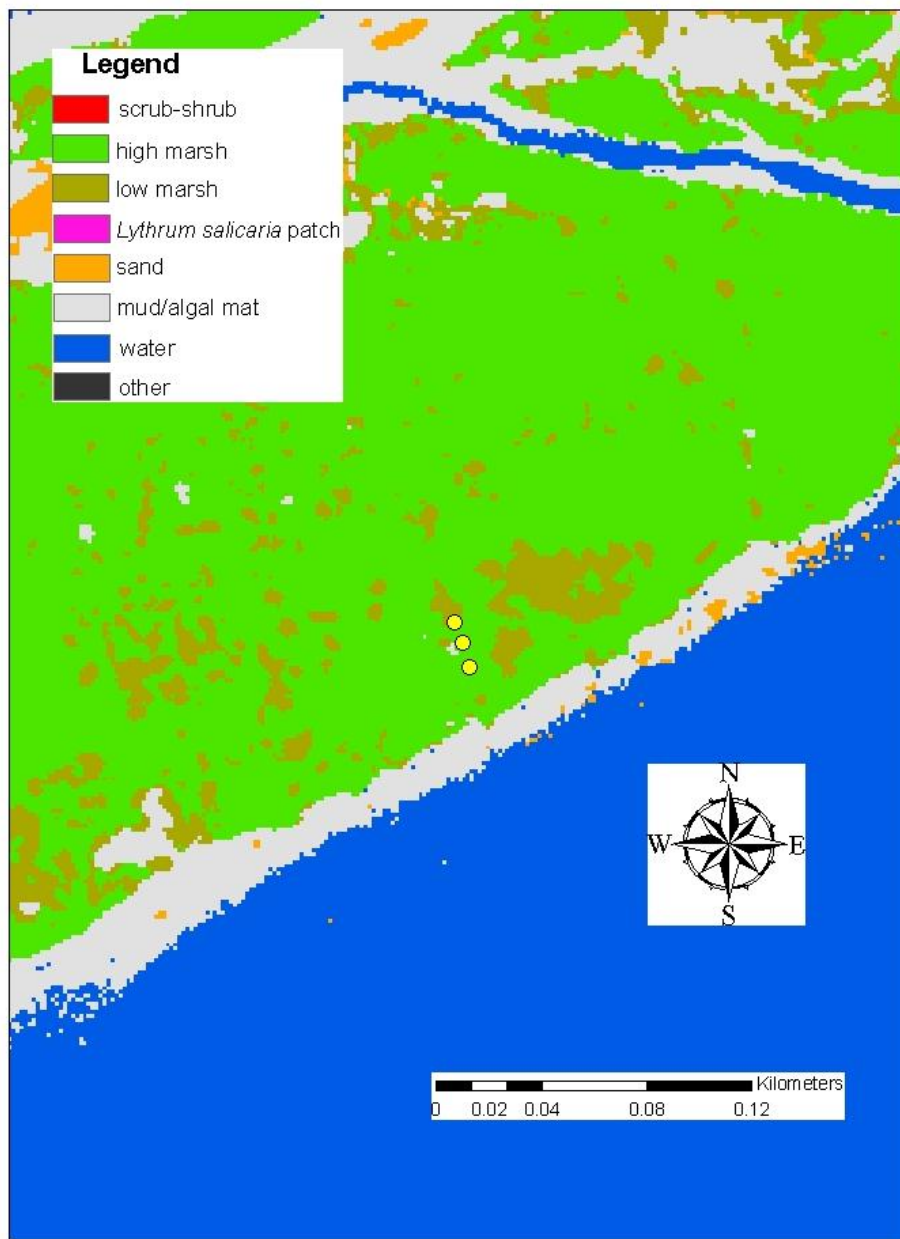
Species locations on the ordination diagram are identified by the first two letters of genus and the first two letters (or unique letters if the first two are the same for two species) of the specific epithet (see Appendix H for codes). Stands are shape coded and color coded according to TWINSpan group [L, ML, M, H, SS]. Individual plots are labeled with their location code (e.g. nw) followed by the sampling station number, followed by the quadrat number.

## Appendix K: Magnified CASI image at Russian Island study sites and comparison to field study results.

The accuracy of the CASI imagery was checked by comparing its interpretation of the habitat classes at the Russian Island study sites with my findings from the in-depth field study of the plant assemblages at each location. Figures K1 through K4 show the magnified CASI image at each of my sites, IMM, INT, DIM, and STBL respectively.

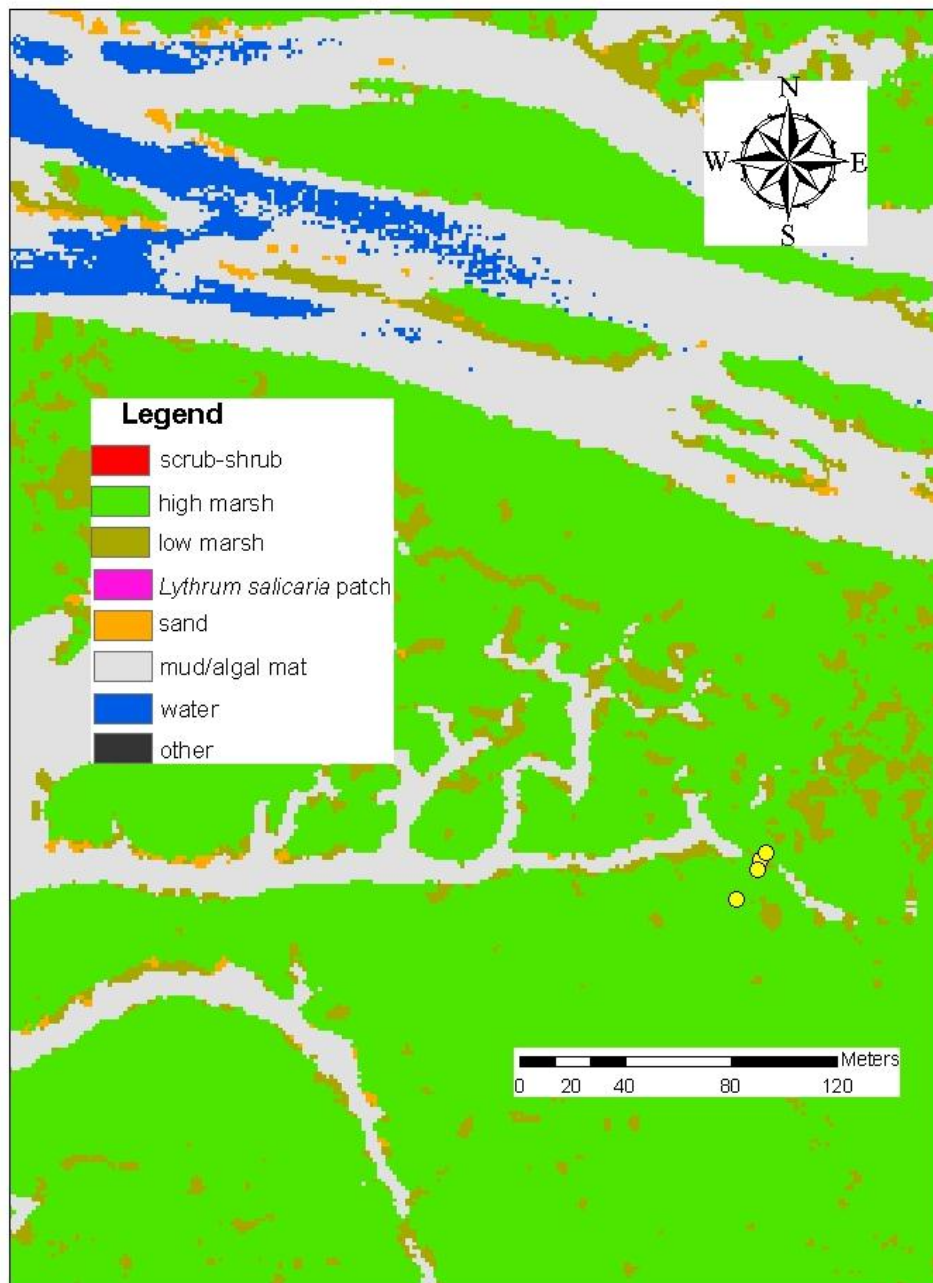
The CASI imagery depicts the plant assemblage at the IMM site relatively accurately, with the presence of a high amount of low marsh habitat (Figure K1). However, the large extent of invasive species, namely *Lythrum salicaria* and *Phalaris arundinacea*, is not represented by the imagery.





**Figure K1. Revised CASI image magnified at IMM Russian Island study site.**

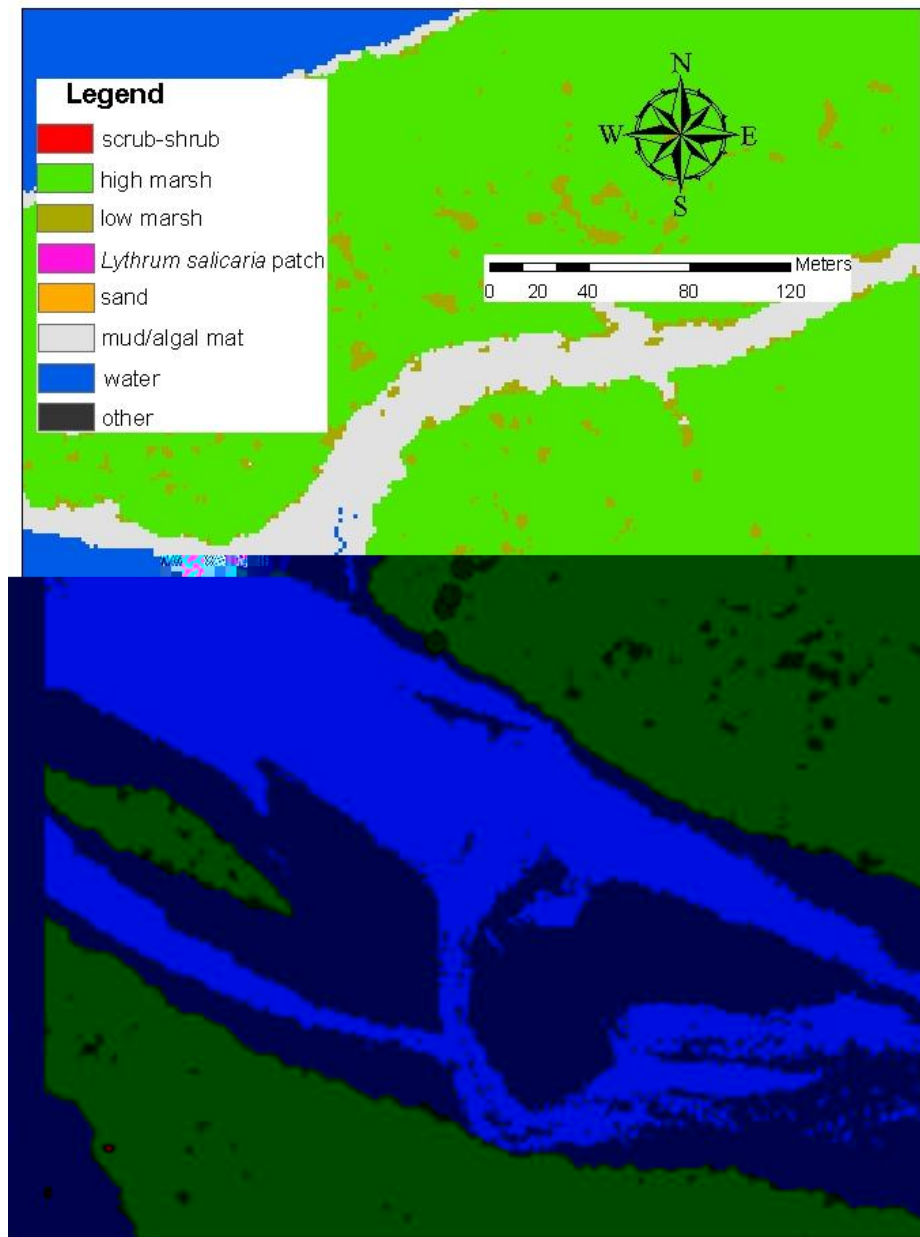
The depiction of the plant assemblage at the INT site by the CASI image is relatively consistent with my findings, with the presence of both high and low marsh habitats (Figure K2). However, the small scrub-shrub (*Salix*) presence at the INT4 sampling station is not detected.



**Figure K2. Revised CASI image magnified at INT Russian Island study site.**

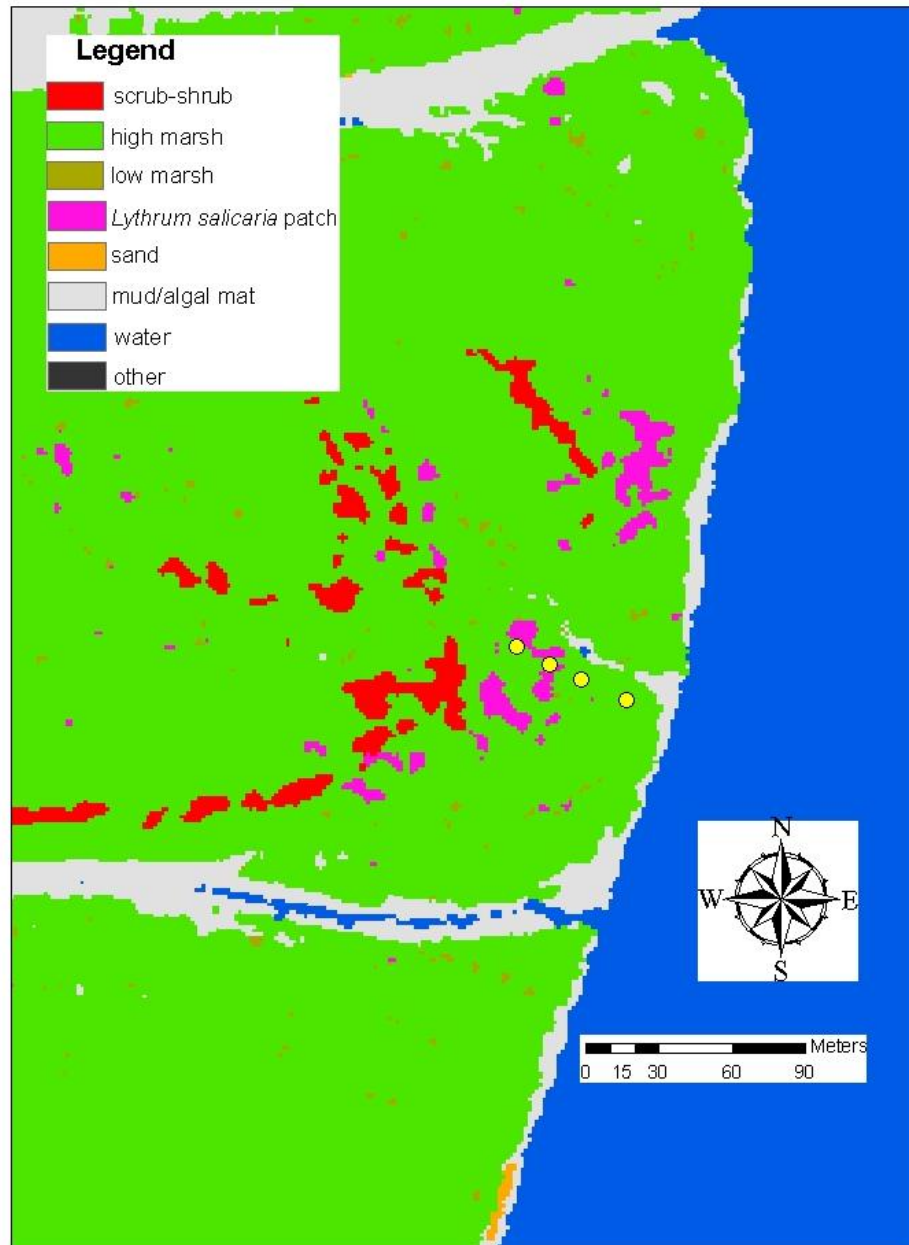
**Individual sampling stations at INT site are denoted by yellow points.**

The depiction of the plant assemblage at the DIM site by the CASI image is also relatively consistent with my findings, with the presence of both high and low marsh habitats (Figure K3). However, the small scrub-shrub (*Salix*) presence at the DIM3 sampling station is not detected.



**Figure K3. Revised CASI image magnified at DIM Russian Island study site. Individual sampling stations at DIM site are denoted by yellow points.**

The depiction of the plant assemblage at the STBL site by the CASI image is also fairly consistent with my findings, in that it shows the presence of high marsh habitat and *Lythrum salicaria* (Figure K4). However, although scrub-shrub areas are shown near my sampling stations in the image, it does not show the STBL4 site as being in same location as the extensive willow stand.



**Figure K4. Revised CASI image magnified at STBL Russian Island study site.**

In summary, the revised CASI image and my field study results corroborate each other when comparison is made at the level of resolution consistent with the CASI. Many of the discrepancies that are found could be due to the temporal difference between the two vegetation assessment methods: the CASI was produced in 2001 and my field study was conducted in 2003. Also, CASI has an extremely high spectral resolution (1.5 m), but its spatial accuracy is not as good (~20 m), which

could also account for discrepancies between the two techniques (i.e., the STBL4 sampling station, which was in the middle of a *Salix* stand, was depicted as being located ~20 m from the scrub-shrub assemblage in the CASI image).

A consistent limitation of the revised CASI image is its lack of ability to detect the small-scale differences in plant assemblages found in my field study, which produced 5 habitat classes (L, ML, M, H, SS) as opposed to three (low marsh, high marsh, and scrub shrub) in the CASI. Also, within-site variability in the plant community (differences between sampling stations) is not represented in the CASI image, such as the distinct plant assemblage dominated by *Lotus corniculatus* and *Myosotis laxa* found at the INT2 site believed to be due to suppression of *Carex lyngbyei* by goose grazing (rest of the site is dominated by *Carex lyngbyei*). The lack of the CASI to detect the small scrub-shrub presence at the DIM and INT sites may be due to the difference in assessment times, as mentioned earlier. The willow trees just may not have been established in 2001 when the CASI image was produced, which isn't impossible given that their maximum height was about 2.5 m.

One main flaw of the CASI image is its lack of accuracy in displaying the extent of invasive species on Russian Island. For example, the spectral signature assigned to *Phalaris arundinacea* was not at all detected on Russian Island. Given the large degree to which this species is present on the island, temporal differences between the two techniques would not account for its complete absence in the CASI image (i.e., this species could not have established and reached its current high abundance in less than three years). Also, according to the CASI image, *Lythrum salicaria*, is only present on the eastern third of the island. Field observations contradict this, with an obvious presence of this species on most parts of the island. This discrepancy could potentially be due to the lag in flight line times related to tidal fluctuations (i.e., different tidal levels on the marsh plus changes in sun angle would cause variations in spectral signatures). Such an explanation is bolstered by the presence of distinct transitions in the array of classes at flight line boundaries (indicated by the no-data swaths) (Figure 18).